NASA CR-166,141

NASA CONTRACTOR REPORT 166141

NASA-CR-166141
19820018996

Advanced Electrochemical Depolarized Concentrator Cell Development

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T. M. Hallick
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Life Systems, Inc.

CONTRACT NAS2-10204
December 1981

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Life Systems, Inc.

Prepared for
Ames Research Center
under Contract NAS2-10204

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

N82-26872 #

FOREWORD

The development work described herein was conducted by Life Systems, Inc. at Cleveland, OH, under Contract NAS2-10204, during the period of April, 1979 through December, 1981. The Program Manager was Franz H. Schubert. The personnel contributing to the program and their responsibilities are outlined below:

Personnel	Area of Responsibility
Kenneth A. Burke	Test Stand Design and Checkout
Steve Czernec	Mechanical Component/System Assembly and Checkout
Robert W. Ellacott	Electrochemical Cell Assembly
George S. Ellis	Mechanical Component Design and Checkout
Tim M. Hallick	Program Testing, Data Reduction, Module/Cell Configurations
John O. Jessup	Test Stand Assembly, Electronic Controller Assembly
Don W. Johnson	Electronic Assembly and Checkout
Eugene Koszenski	Electrode/Matrix Fabrication, Project Management
J. David Powell	In Situ Cell Maintenance Analysis, Component Controller Design
Franz H. Schubert	Program Manager, System Analysis and Design
Richard R. Woods, Jr.	Supporting Technology Studies, Electrochemical and Chemical Performance Analysis, Composite Cell Technology
Rick A. Wynveen, Ph.D.	Program Administration, Electrochemical Support Concept Evaluations

The contract's Technical Monitor was P. D. Quattrone, Chief, Advanced Life Support Office, NASA Ames Research Center, Moffett Field, CA.

Performance characterization of a Bosch CO_2 Reduction Subsystem was also conducted by Life Systems, Inc. for the NASA Ames Research Center as part of this contract. The period of performance for that portion of the total program was June, 1979 to January, 1980. The development work was described and previously submitted in Life Systems' Final Report, "Performance Characterization of a Bosch CO_2 Reduction Subsystem," LSI TR-379-11, NASA CR-152342. The Program Manager was Dennis B. Heppner, Ph.D.

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LIST OF ACRONYMS

ADC	Analog to Digital Converter
ALSS	Advanced Life Support System
ARS	Air Revitalization System
BID	Build-in Diagnostic
CCA	Coolant Control Assembly
CG	Combustible Gas
C/M I	Control/Monitor Instrumentation
CRT	Cathode Ray Tube
CS-1	One-Man CO_2 Concentrator
DAS	Data Acquisition System
DARS	Data Acquisition and Reduction System
DMA	Direct Memory Access
DVT	Design Verification Test
EDC	Electrochemical Depolarized CO_2 Concentrator
EDCM	EDC Module
EDO	Extended Duration Orbiter
FCA	Fluid Control Assembly
HX	Heat Exchanger
I/O	Input/Output
ISCM	In Situ Cell Maintenance
LP	Line Printer
LRC	Line Replaceable Component
LRU	Line Replaceable Unit
LSI	Life Systems, Inc.
M/EA	Mechanical/Electrochemical Assembly
NASA	National Aeronautics and Space Administration
OpC	Operational Controller
PFC	Power Failure Controller
PID	Proportional, Integral, Differential
POR	Power On Reset
RH	Relative Humidity
RHCM	Relative Humidity Controller and Monitor
RTE	Real Time Executive
S/D	Shutdown
TeCM	Temperature Controller and Monitor
TSA	Test Support Accessories
VPI	Valve Position Indicator
WVEM	Water Vapor Electrolysis Module

SUMMARY

Regenerative carbon dioxide removal techniques are needed to sustain man in space for extended periods of time. The most promising concept for a regenerative carbon dioxide removal system is the Electrochemical Depolarized Carbon Dioxide Concentrator. This device allows for the continuous, efficient removal of carbon dioxide from the spacecraft cabin atmosphere and delivery of the carbon dioxide premixed with hydrogen to a Carbon Dioxide Reduction Subsystem for subsequent oxygen recovery.

The objectives of this program for the Electrochemical Depolarized Carbon Dioxide Concentrator Subsystem were to (1) achieve reproducibility and predictability of high level performance over wider ranges in relative humidity and hydrogen backpressures both at the electrochemical cell and module level; (2) simplify and increase subsystem reliability by minimizing and/or combining ancillary components; (3) demonstrate achievement of reproducible electrochemical cell and module performance and subsystem simplification concepts through extensive testing; and (4) continue to improve overall Subsystem performance. These objectives were successfully met. The program included (1) the design of an advanced one-person Carbon Dioxide Removal Subsystem and development and evaluation of (2) a full-scale (six-cell), Electrochemical Depolarized Carbon Dioxide Concentrator module with unitized core composite cells, (3) a Fluids Control Assembly, that integrates eleven discreet components, (4) a Coolant Control Assembly that replaces three components and interconnecting plumbing and (5) Test Support Accessories and instrumentation required for component testing and required test stands and test setups. A detailed hardware concept for automatic electrical isolation of degraded Concentrator cells was also developed, and an improved facility for electrolyte charging of Concentrator cells was developed and tested.

Parametric testing of the six-cell module demonstrated high level, repeatable performance over 3,000 hours of operation and relative humidity variations between 16 and 72%. Average carbon dioxide removal efficiency was typically greater than 90%, (versus the 80% design point) at a nominal carbon dioxide partial pressure of 400 Pa (3.0 mm Hg). This cell construction voltage was 0.4 V. The cell could sustain 965 kPa (140 psid) (non-operational) hydrogen/air differential pressures with no leakage across the cell matrix.

The Coolant Control Assembly performed at or above design point levels over 700 typical test cycles. Post-test inspection of the unit revealed all components to be in good condition. Satisfactory mechanical performance of the Fluids Control Assembly was observed over 30 days of continuous testing and nearly 200 complete valve cycles, except for some minor, intermittent leakage in one valve position remediable by increased O-ring compression and/or less critical indexing tolerance. Post-test inspection revealed no O-ring wear or damage.

The six-cell module test stand provided a high degree of sophistication with respect to automatic fault detection and startup sequencing. The test stand enabled unattended operation of the module/components for extended time periods. The new electrolyte charging facility performed as designed.

PROGRAM ACCOMPLISHMENTS

The key program accomplishments were as follows:

- Completed the design of a one-person Electrochemical Depolarized Carbon Dioxide Concentrator (EDC) Subsystem incorporating advanced electrochemical, mechanical and Control/Monitor Instrumentation (C/M I) concepts. This subsystem called the CS-1, included design of an advanced liquid-cooled unitized core/composite cell EDC module (EDCM) that will feature superior performance stability, inlet air relative humidity (RH) range, pressure capability and thermal characteristics and lower unit weight and volume relative to previous modules.

- Developed and tested a liquid-cooled unitized core/composite cell EDCM, based on modified baseline cell frames and nonintegral air temperature preadjustment - a precursor to the CS-1 module. Observed high performance stability (greater than 90% carbon dioxide (CO_2) removal efficiency for 3,000 hours) over broad RH ranges (16 to 72%) and demonstrated no-leak operational differential pressure capability at 103 kPa (15 psid).

- Completed the development, design, fabrication and successful testing of a prototype Fluids Control Assembly (FCA), which integrates eleven gas handling components required by the CS-1 Subsystem into a single unit.

- Completed the breadboard development, design, fabrication and successful testing of a prototype Coolant Control Assembly (CCA), which integrates the coolant pump, diverter valve and accumulator of the liquid-cooled EDC-based CS-1 subsystem into a single unit.

- Developed a test stand that fulfills all the fluid, electrical and automatic instrumentation requirements for long term, unattended testing of a six-cell EDCM.

- Completed a detailed definition of in situ cell maintenance concept for the CS-1 EDCM that will permit automatic electrical isolation of degraded cells without interrupting subsystem operation.

- Completed the design, fabrication and testing of an improved EDCM electrolyte charge fixture.

INTRODUCTION

Regenerative processes for revitalization of spacecraft atmospheres are essential for the realization of making long-term manned space missions. An important air revitalization step is the collection and concentration of metabolically-produced CO_2 for subsequent oxygen (O_2) recovery. This report discusses development of an advanced EDC subsystem to perform that function.

Background

The EDC technique is the most promising technique for concentrating low level CO_2 from the air without incurring large weight and volume penalties. The EDC removes CO_2 continuously from a flowing air stream. The CO_2 exits the EDC premixed with hydrogen (H_2), which can be sent to a CO_2 reduction subsystem for recovery of O_2 from the CO_2. The EDC also generates electrical power that can be utilized in other life support processes (e.g., water electrolysis) if desired.

The CO_2 removal takes place in a module consisting of a series of electrochemical cells. Each cell consists of two electrodes separated by a matrix containing an aqueous carbonate electrolyte solution. Plates adjacent to the electrodes provide passageways for distribution of gases and electrical current. Figure 1 shows a functional schematic of the EDC cell. Figure 2 details the specific electrochemical and chemical reactions. As shown in Figure 2, the overall reaction is:

$$O_2 + 2CO_2 + 2H_2 = 2CO_2 + 2H_2O + \text{electrical energy} + \text{heat} \qquad (1)$$

A theoretical maximum of two moles of CO_2 can be transferred for one mole of O_2 consumed. The observed ratio of CO_2 transferred to O_2 consumed represents the process removal efficiency. A defined efficiency of 100% occurs when 2.75 kg (6.05 lb) of CO_2 is removed for each kg (2.2 lb) of O_2 consumed.

The EDC concept utilizing alkaline metal carbonate electrolytes has evolved at Life Systems, Inc. (LSI) under NASA sponsorship through Contracts NAS2-6118, NAS2-6478 and NAS2-8666.[1-5] The concept has progressed from operation of a single cell to fabrication and testing of one-, three-, four- and six-person self-contained subsystems. These previous research and development activities resulted in demonstrated performance improvements in the electrodes, the electrolyte and the electrolyte-retaining matrix. These programs also included development of unique peripheral components and advancement of technology relating to EDC subsystem integration with other spacecraft air revitalization subsystems.

Program Objectives

The objectives of this program were to:

1. Achieve reproducible and predictable high level EDC performance over wider than previously demonstrated ranges in relative humidity (RH) and H_2 backpressures, both at the electrochemical cell and module levels.

2. Simplify and increase EDC subsystem reliability by minimizing and/or combining ancillary components.

3. Demonstrate achievement of reproducible electrochemical cell and module performance and subsystem simplification concepts through extensive testing.

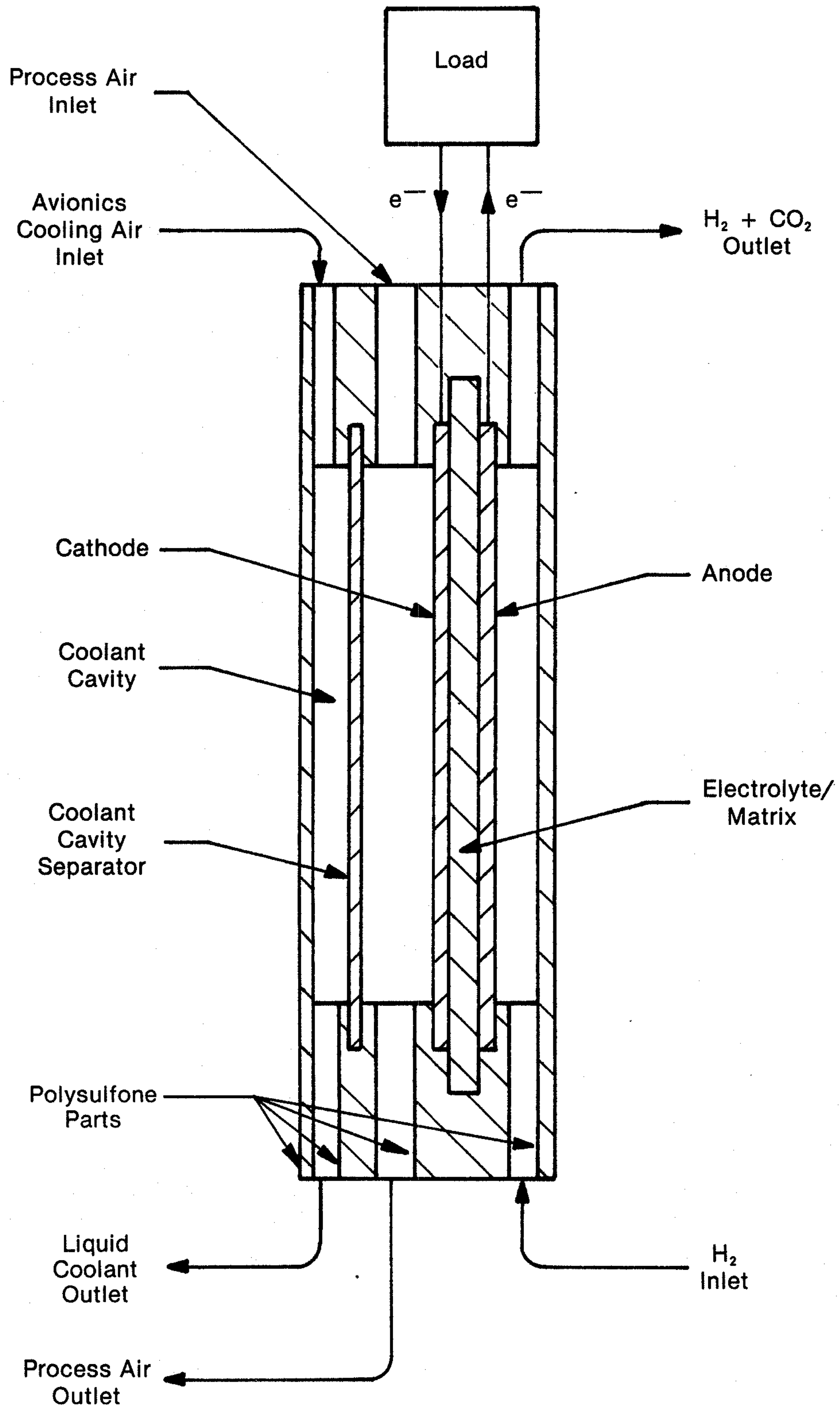
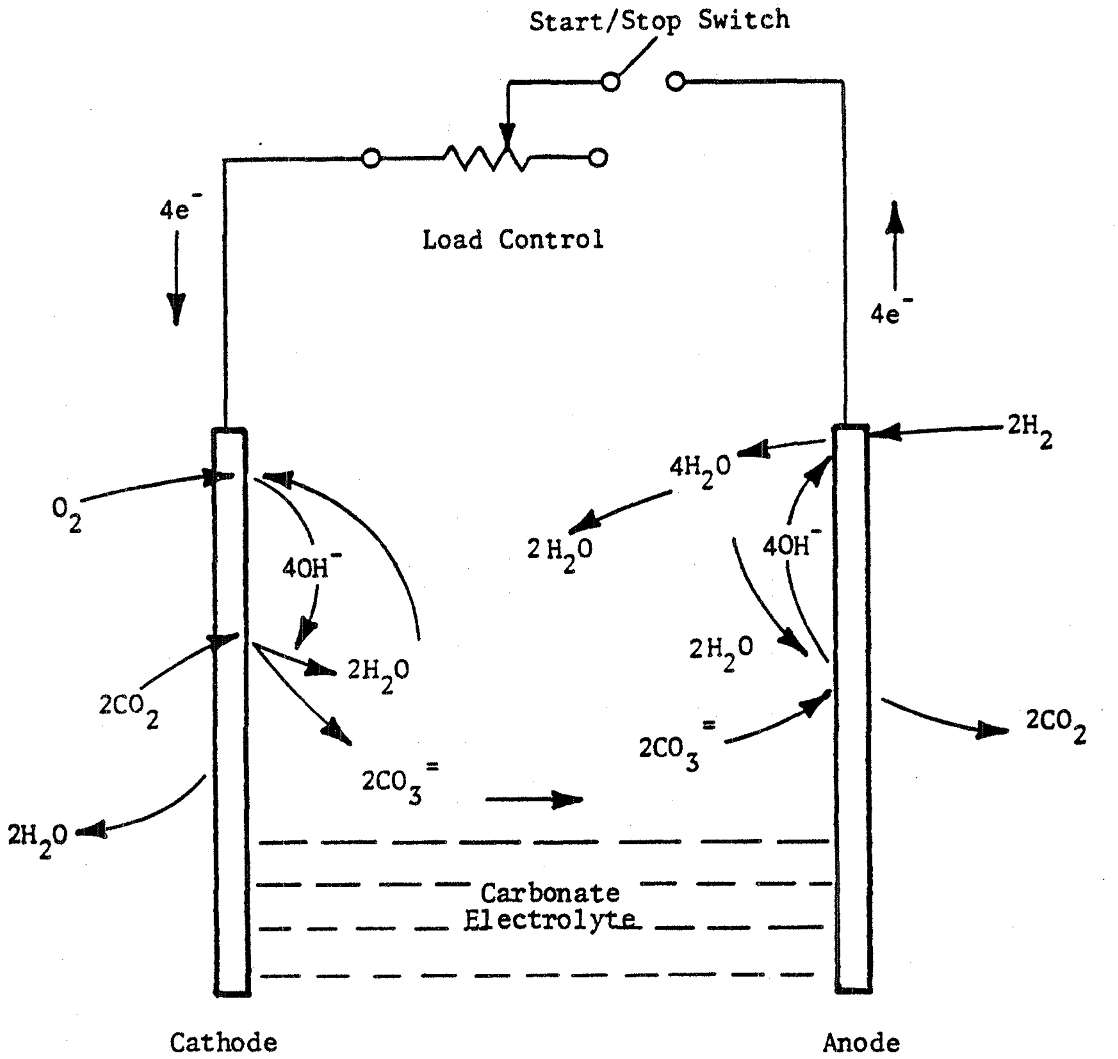


FIGURE 1 EDC SINGLE-CELL SCHEMATIC



Cathode Reactions:

$$O_2 + 2H_2O + 4e^- = 4OH^-$$
$$4OH^- + 2CO_2 = 2H_2O + 2CO_3^=$$

Anode Reactions:

$$2H_2 + 4OH^- = 4H_2O + 4e^-$$
$$2CO_3^= + 2H_2O = 4OH^- + 2CO_2$$

Overall Reaction:

$$O_2 + 2CO_2 + 2H_2 = 2CO_2 + 2H_2O + \text{Electrical Energy} + \text{Heat}$$

FIGURE 2 EDC FUNCTIONAL SCHEMATIC WITH REACTIONS

4. Continue to improve EDC subsystem performance.

The objectives of the program were met.

Report Organization

This Final Report covers the work performed during the period April, 1979 through December, 1981. The following six chapters of this report present the technical results grouped according to:

- Subsystem Design
- Primary Subsystem Component Development (three separate chapters)
  - Unitized Core Electrochemical Cell Developments
  - Fluid Control Assembly Development
  - Coolant Control Assembly Development
- Technology Advancement Studies
- Mini-Product Assurance Program

These sections are followed by Conclusions and Recommendations based upon the work performed and by References cited in the text.

ONE-PERSON CARBON DIOXIDE REMOVAL SUBSYSTEM DESIGN

Achievement of program objectives included the design of a complete one-person CO_2 removal subsystem, the CS-1, integrating the advanced technologies developed in the subject program and a sophisticated C/M I unit. This chapter describes that design. Following chapters discuss component developments.

General Description

The overall CO_2 removal process and control scheme is described in Figure 3. The Mechanical/Electrochemical Assembly (M/EA) includes a six-cell EDCM and all components required to sense and control gaseous and liquid fluid flows to and from this module. The C/M I controls overall subsystem operation through the sensors and actuators of the M/EA. The C/M I also monitors, interprets and displays subsystem operational parameters, and provides appropriate changes in operational modes in response to operator inputs or subsystem malfunctions.

Applications

Two applications considered at present for the CS-1 include use in the Shuttle Orbiter and as part of a central air revitalization system (such as in a space station). The design focused primarily on the former application, which makes much greater demands on subsystem operating range. These demands are apparent in the design specifications discussed below.

Specifications

General design specifications are listed in Table 1 and Figure 4. The RH/temperature range projected for the Shuttle application[6] is broad because

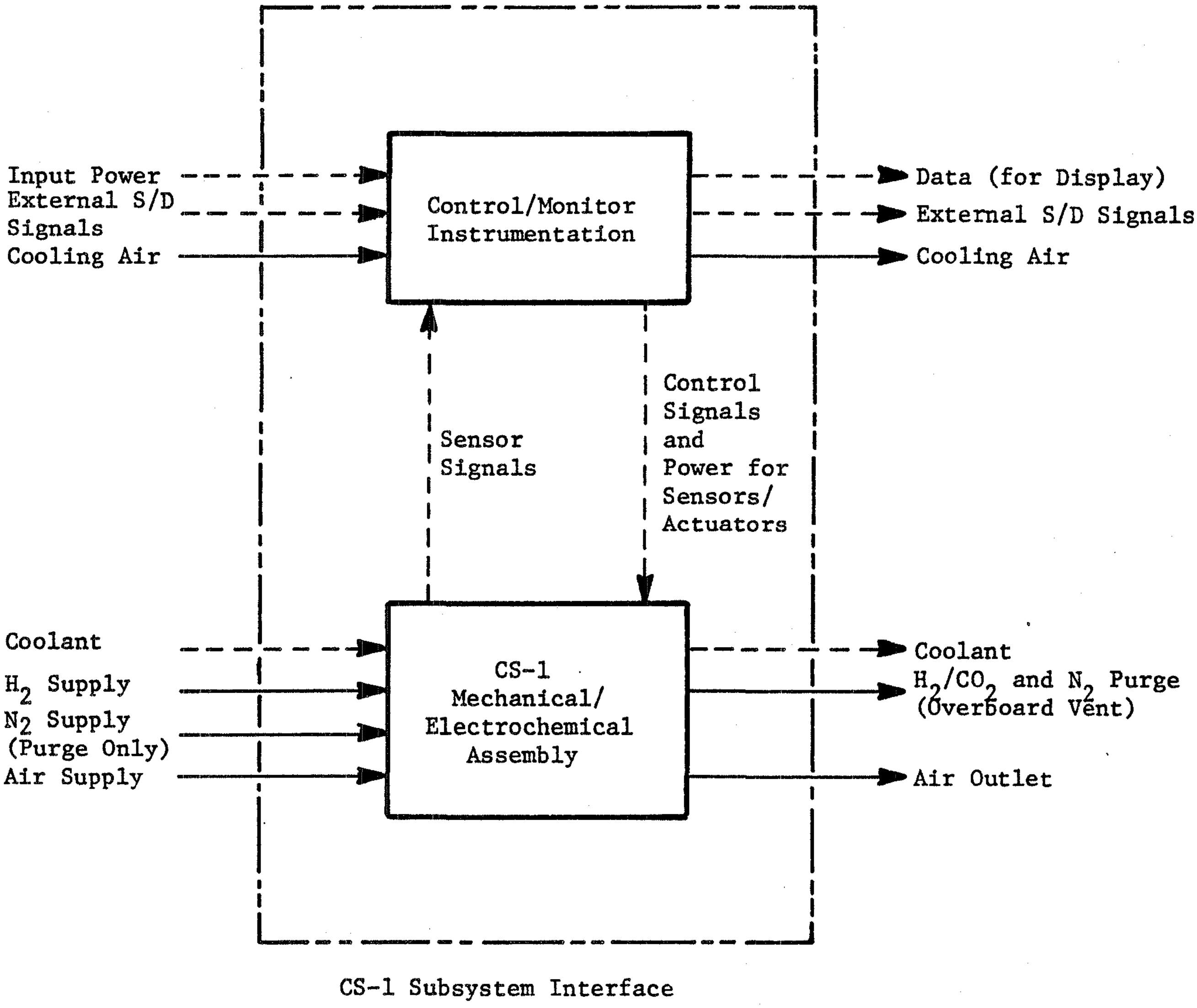


FIGURE 3 CS-1 PROCESS BLOCK DIAGRAM

TABLE 1 CS-1 DESIGN SPECIFICATIONS

	Application: Shuttle	Central[a]
Crew Size	1	--
CO_2 Removal Rate, kg/h (lb/h)	0.040 (0.088)	--
Cabin pCO_2, Pa (mm Hg)		
Daily Average	667 (5.0)	400 (3.0)
Maximum	1.013 (7.6)	667 (5.0)
Cabin pO_2, kPa (psia)	22.1 (3.2)	--
Cabin Temperature, K (F)	291 to 302 (65 to 84)	291 to 300 (65 to 80)
Cabin Dew Point, K (F)	277 to 289 (39 to 61)	279 to 294 (42.5 to 69)
Cabin Pressure, kPa (psia)	101 (14.7)	--
Process Air Humidity Range	See Figure 4	--
Liquid Coolant		
Temperature (max), K (F)	275 to 295 (35 to 71)	280 (45)
Flow Rate, kg/h (lb/h)	432 (950)	--
H_2 Supply		
Flow Rate, kg/h (lb/h)	0.003 (0.006) 1.2 Stoichiometric (at 9.0 Amperes)	0.007 (0.014) 2.9 Stoichiometric (at 9.9 Amperes)
Pressure, Pa (psia)	173 (25)	--
Relative Humidity, %	0 to 5	0 to 75
Purge Gas		
Type	N_2	--
Pressure, kPa (psia)	173 (25)	--
Electrical Power, VAC	115, 60 Hz, 1Ø[b] 115, 400 Hz, 1Ø	-- --
Gravity	0 to 1	--
Noise Criteria, db	55[c]	--

(a) By exception only. Specifications not indicated are the same as for the Shuttle.
(b) Both 400 Hz and 60 Hz power is used but is not concept limiting where only 400 Hz power is available.
(c) Difficult to meet and will be met in flight hardware.

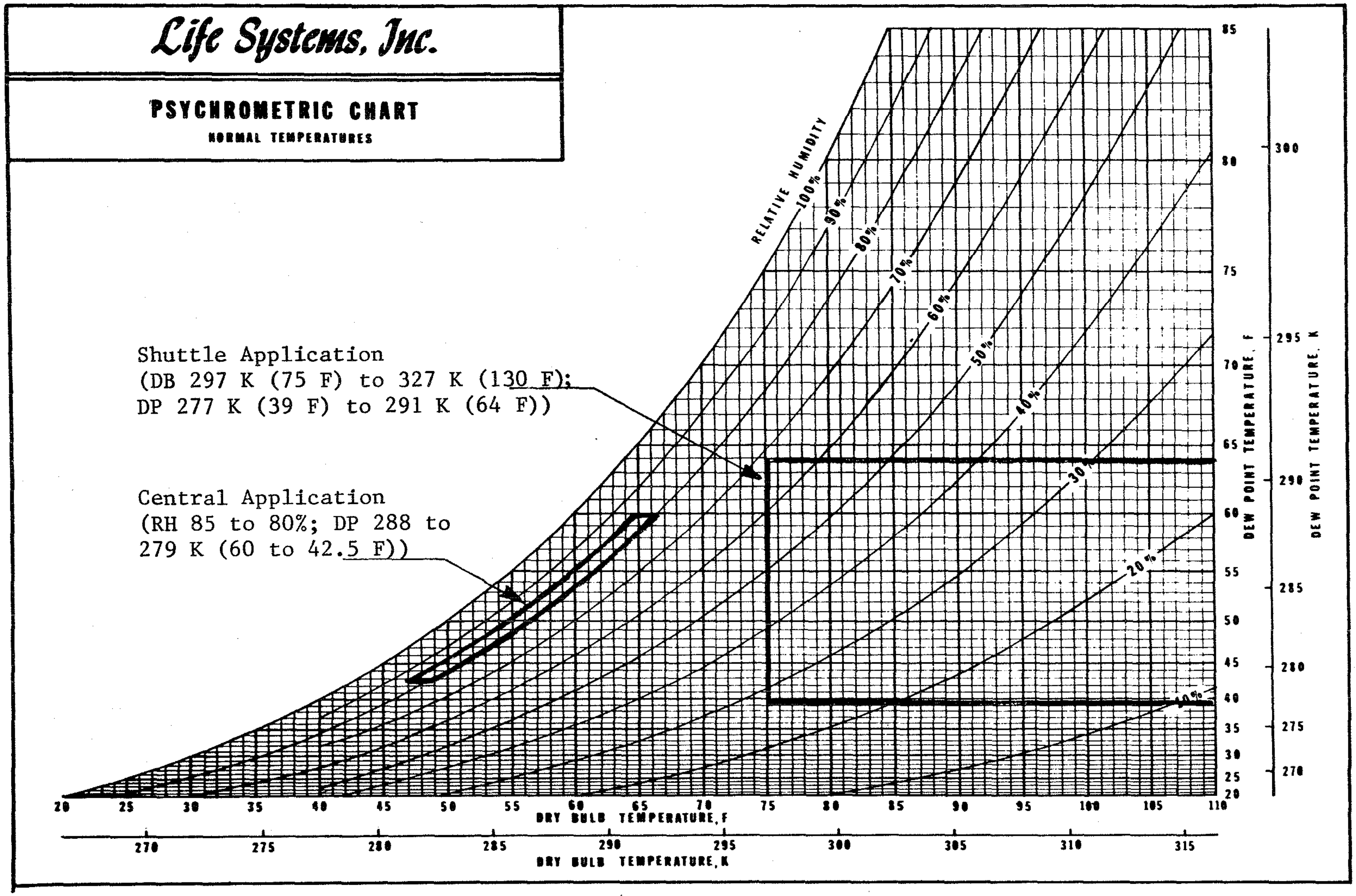


FIGURE 4 PROCESS AIR HUMIDITY RANGES TO CS-1 FOR BOTH CENTRAL AND SHUTTLE APPLICATIONS

the CS-1 will be located upstream of the spacecraft's condensing heat exchanger and the RH and temperature of air entering the subsystem will be completely unregulated. (In contrast, the CS-1 would be located downstream of the condensing heat exchanger in a central air revitalization system.) Fluid electrical and thermal inputs and outputs for the Shuttle CS-1 are further illustrated in Figure 5.

Subsystem Operating Modes

Four operating modes will be available for the subsystem, as shown in Figure 6, with separate normal modes corresponding to the operating conditions of either Shuttle or central applications. Each mode is defined in Table 2.

Mechanical/Electrochemical Assembly

The M/EA is illustrated schematically in Figure 7. Each of the primary components is described briefly below.

- The EDCM is the CO_2 concentration element. Current produced by this module is regulated through the Current Controller (liquid-cooled).
- The FCA regulates module backpressure and H_2 and N_2 flows.
- The CCA, in conjunction with the Liquid/Liquid Heat Exchanger, permits temperature regulation of the EDCM.

Figure 8 schematically describes the CS-1 in more detail (symbols are listed in Table 3). In addition to the primary components, two of which integrate several discreet device functions, the subsystem includes temperature and dew point sensors to permit monitoring and control of temperature and RH and a combustible gas sensor for H_2 safety. It is projected that these sensors will be triply redundant for increased reliability.

Figure 9 describes the projected dimensional configuration of the CS-1. Table 4 summarizes its projected weight, power and heat rejection requirements.

The principal M/EA components are described further below.

Advanced EDC Module

The advanced EDCM was designed as a liquid-cooled module, composed of six unitized core composite cells for superior performance and differential pressure capability. Each composite cell consists of electrochemical elements bonded together into an integral unit (the unitized core) and sealed into a specially designed cell frame. The selected number of cells, six, was based on the one-person level CO_2 removal rate of 1.0 kg/d (2.2 lb/d) and a conservatively low current density of 21.5 mA/cm^2 (20 ASF) for high efficiency (see Figure 10). The next chapter of this report details the development and demonstrated superior performance of unitized core cells (presently using modified baseline cell frames) and evaluation of a full-scale module.

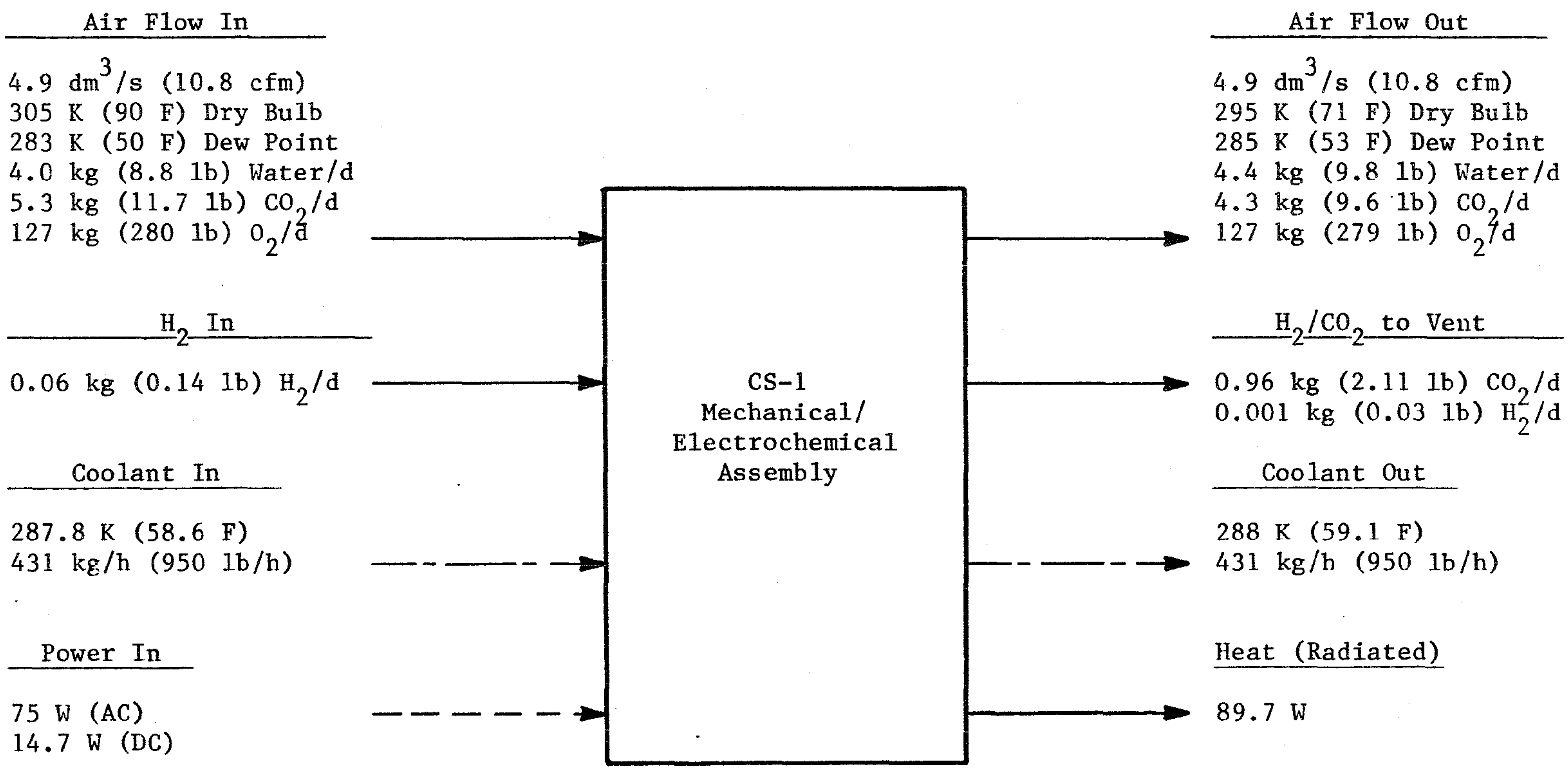
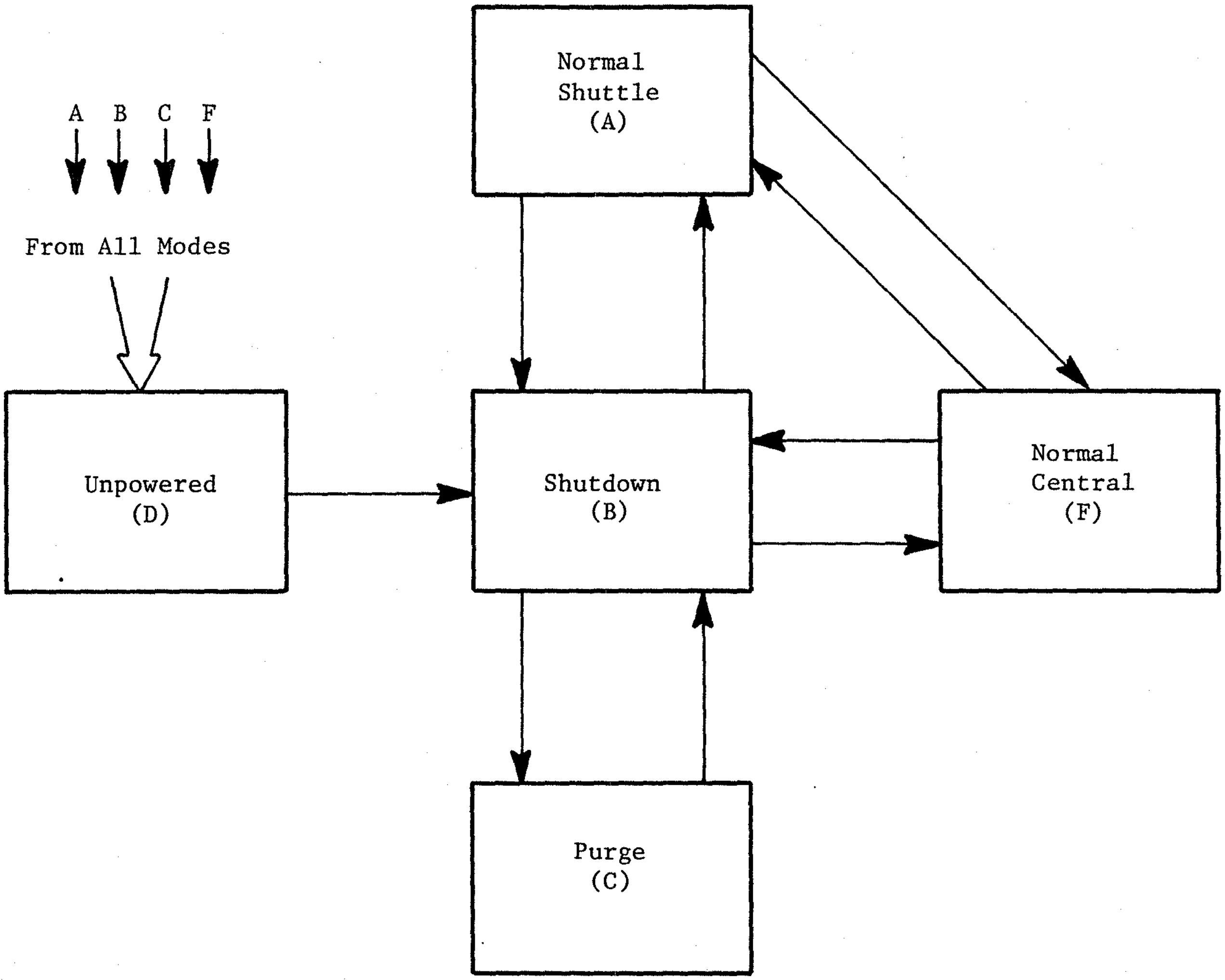


FIGURE 5 CS-1 MASS AND ENERGY BALANCE



- 5 Modes
- 4 Operating Modes
- 13 Mode Transitions
- 9 Programmable, Allowed Mode Transitions

FIGURE 6 CS-1 MODES AND ALLOWABLE MODE TRANSITIONS

TABLE 2 CS-1 MODE DEFINITIONS

Mode (Code)	Definition
Shutdown (B)	The EDCM is not removing CO_2. Module current is zero, the coolant pump is off and all valves are closed. The system is powered and all sensors are working. The Shutdown Mode is called for by: • Manual actuation • Low EDCM individual cell voltage • Low H_2 pressure • High H_2 pressure • Low outlet process air RH • High outlet process air RH • High combustible gas concentration (not included • Second failure of triple redundant sensors for pressure, relative humidity, temperature and combustible gas concentration (capability only) • Power on reset (POR) from Unpowered Mode (D) • Mode transition from Shutdown Mode (B) to Normal Shuttle (A), Normal Central (F), or Purge (C) was not successful. All transitions to the Shutdown Mode except POR and Purge include a timed purge sequence as part of the mode transition sequence.
Normal Shuttle (A)	- Constant Current Control Method (IA) The EDCM is operating at the constant current density of 19.4 mA/cm^2 (18.0 ASF) sized to perform the CO_2 removal function for one-person assuming an inlet pCO_2 level of 667 Pa (5.0 mm Hg). The Normal Shuttle Mode, IA, is called for by: • Manual actuation - Constant pCO_2 Control Method (IB, capability only) The EDCM is operating at a constant current density from 16.1 mA/cm^2 (15 ASF) to 53.8 mA/cm^2 (50 ASF) and maintains a constant cabin pCO_2 level of 667 Pa (5.0 mm Hg) and is performing its CO_2 removal function between the 0.8 to 1.8 person rate. The Normal Shuttle Mode, IB, is called for by: • Manual actuation (cabability only)

continued-

Table 2 - continued

Mode (Code)	Definition
Normal Central (F)	- Constant Current Control Method (IA) The EDCM is operating at a constant current density of 21.3 mA/cm^2 (19.8 ASF) sized to perform the CO_2 removal function for one-person assuming an inlet pCO_2 level of 400 Pa (3.0 mm Hg). The Normal Central Mode, IA, is called for by: • Manual actuation - Constant pCO_2 Control Method (IB capability only) The EDCM is operating at a variable current density from 16.1 mA/cm^2 (15.0 ASF) to 53.8 mA/cm^2 (50 ASF) and maintains a constant cabin pCO_2 level of 400 Pa (3.0 mm Hg) and is performing its CO_2 removal function between the 0.7 to 1.5 person rate. The Normal Central Mode, IB, is called for by: • Manual actuation
Purge (C)	The EDC is being purged with N_2 through all H_2 lines, H_2 carrying module cavities and out through the overboard vent line. Module current and the coolant pump are off. This is a continuous purge until a new mode is called for or a preset time duration is reached. The Purge Mode is called for by: • Manual actuation
Unpowered (D)	No electrical power is applied to the EDC. Actuator positions can only be verified visually. There may or may not be process air flow. There could be N_2 purge or H_2 flow depending on when the EDC was unpowered. The Unpowered Mode is called for by: • Manual actuation (circuit breaker) • Electrical power failure • C/M I failure as detected by the Built-in Diagnostic (BID) circuit

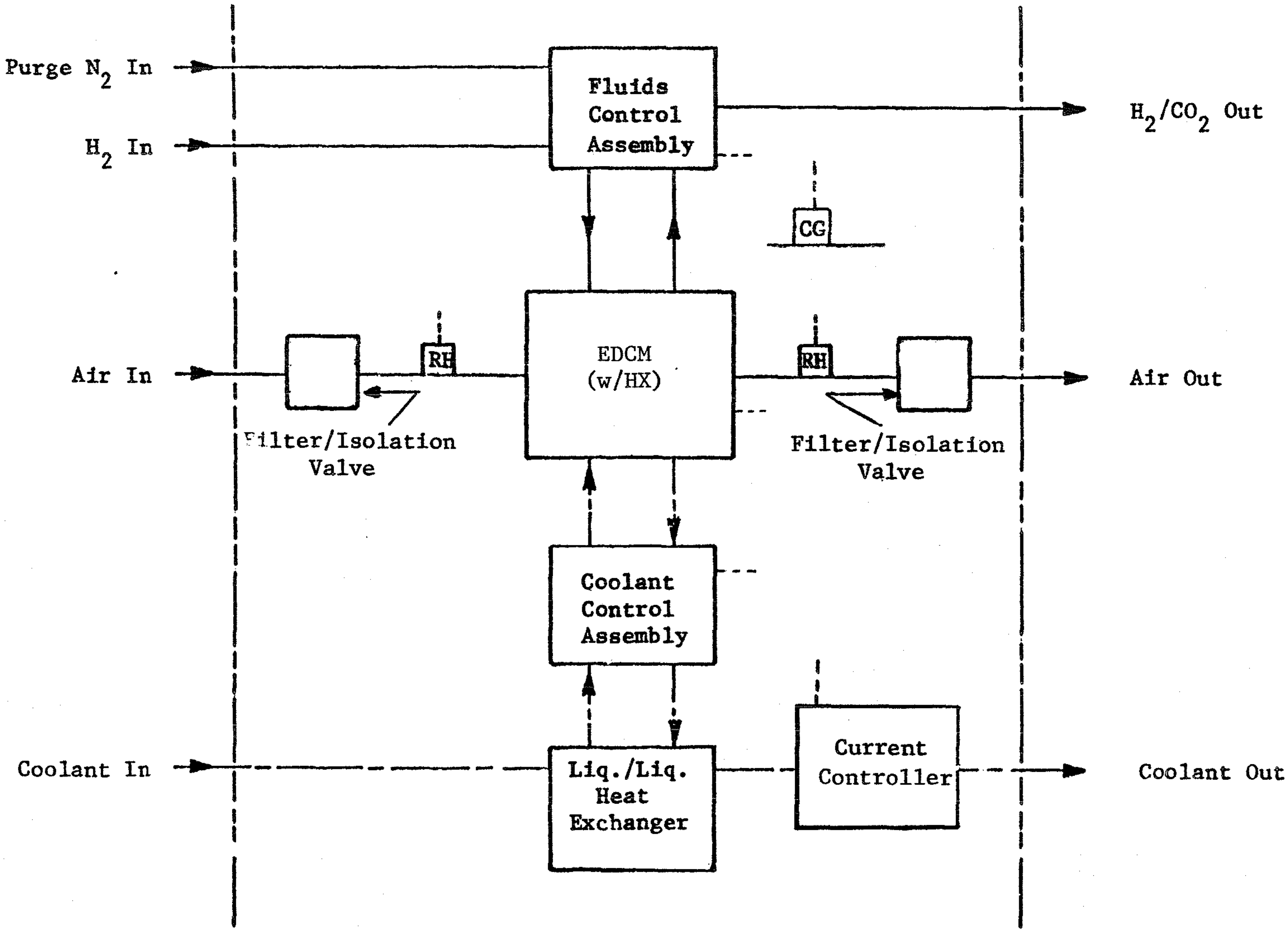


FIGURE 7 CS-1 SCHEMATIC (LEVEL 1) FOR THE SHUTTLE AND CENTRAL APPLICATIONS

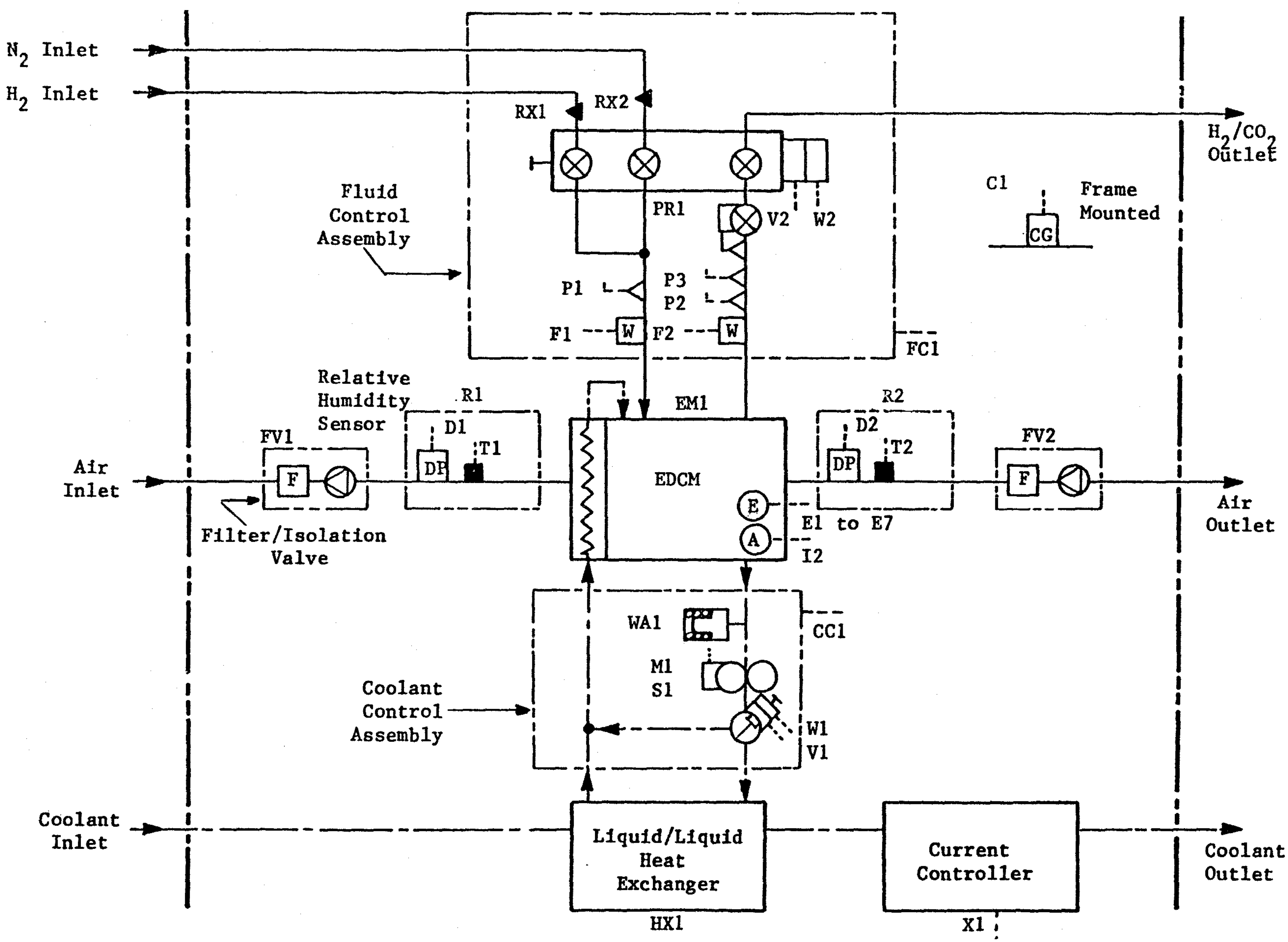
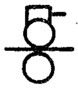
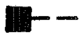
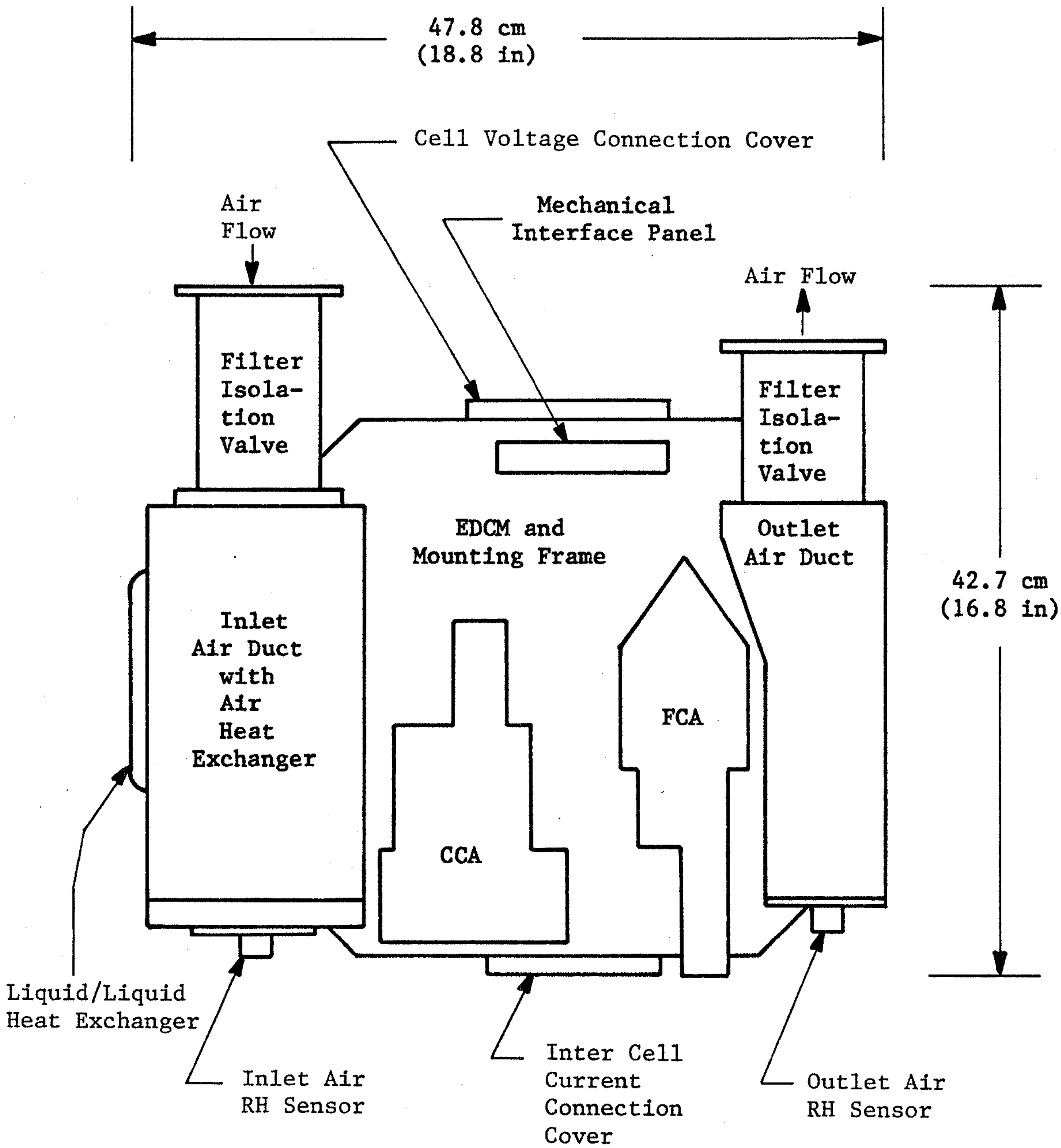


FIGURE 8 CS-1 MECHANICAL SCHEMATIC

TABLE 3 MECHANICAL SCHEMATIC SYMBOLS

Symbol	Description
	Flowmeter
	Manual Shutoff Valve (Normally Open)
	Pressure Sensor
	Pump
	Manual Three Way Valve
	Temperature Sensor
	Heater
	Cooling Coil
————	Gas Line
— — — —	Electrical Line
—— – ——	Liquid Line
	Flow Sensor
Hx	Heat Exchanger
	Timer
HSS	Heat Source Simulator
VPI	Valve Position Indicator



Front Dimensions/Volume	
Height, cm (in)	Volume, dm^3 (ft^3)
30.5 cm (12.0 in)	62 (2.2)

FIGURE 9 CS-1 PACKAGING ILLUSTRATION (TOP VIEW)

TABLE 4 CS-1 MECHANICAL COMPONENT WEIGHT, POWER AND HEAT REFJECTION SUMMARY

Item No.	Component	No. Req'd	Unit Weight,[a] kg (lb)	Total Weight, kg (lb)	Total AC Power, W	Total DC Power, W	Heat Rejection, W
1	EDCM[b]	1	18.2 (40.0)	18.2 (40.0)	---	---[c]	41
2	Assembly, Fluids Control	1	2.8 (6.1)	2.8 (6.1)	---	2[d]	2
3	Assembly, Coolant Control	1	3.7 (8.1)	3.7 (8.1)	75	11[e]	86
4	Heat Exchanger, Liq/Liq	1	0.8 (1.8)	0.8 (1.8)	---	---	---
5	Filter/Isolation Valve	2	0.7 (1.5)	1.4 (3.0)	---	---	---
6	Sensor, RH	2	0.9 (2.0)	1.8 (4.0)	---	1	1
7	Sensor, Combustible Gas	1	0.2 (0.4)	0.2 (0.4)	---	1	1
8	Interface, Inlet Air (W/Heat Exchanger) 3.29 lb for Hx	1	2.3 (5.0)	2.3 (5.0)	---	---	---
9	Interface, Outlet Air	1	0.5 (1.0)	0.5 (1.0)	---	---	---
10	Frame, Mounting	1	0.5 (1.0)	0.5 (1.0)	---	---	---
11	Assembly, Current Controller	1	3.2 (7.0)	3.2 (7.0)	---	1	28[c]
			---	35.2 (77.4)	75	16	159

(a) Wet weight.
(b) Does not have honeycomb end plates.
(c) The 27 W of EDCM power is converted to heat for CS-1 application.
(d) Steady-state operation; when switching 20.9 W (less than 1% of time).
(e) Assumes Diverter Valve controlling continuously.

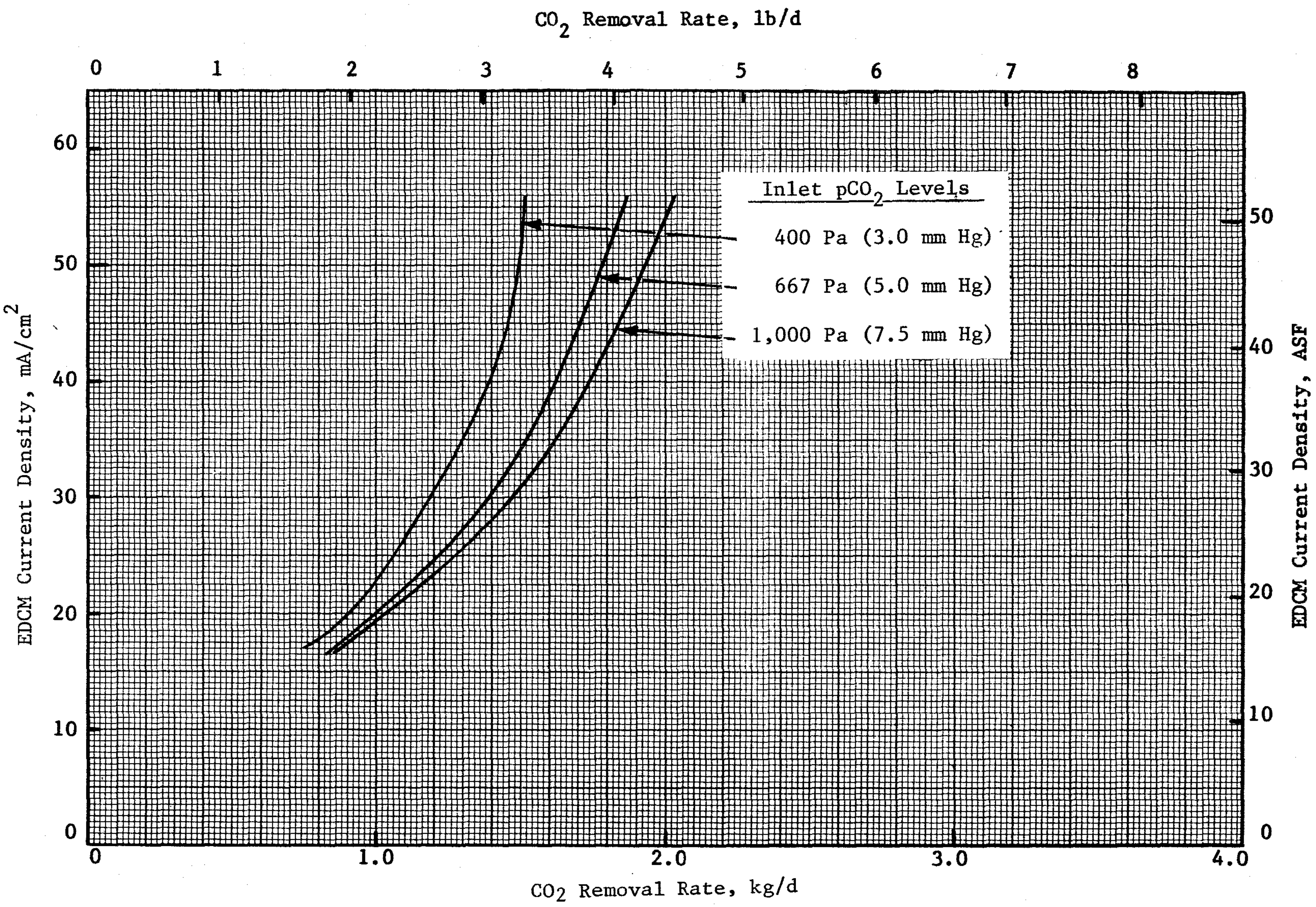


FIGURE 10 REQUIRED EDCM CURRENT DENSITY VERSUS CO_2 REMOVAL RATE

The advanced composite cell frames to be incorporated into the CS-1 feature integral process air manifolds. These are apparent in the module drawing, Figure 11. This design will simplify interfacing with the process air. It should also enhance module storage life by permitting capping of the manifolds to avoid dryout (versus sealing modules in plastic bags) and allow vacuum charging of the total module (versus individual cells) with electrolyte.

The inlet duct attached to the advanced module will contain an integral heat exchanger (shown schematically in Figure 8) that preadjusts process air temperature to module temperature and will therefore provide stable operation at widely varying process air dry bulb temperatures.

The advanced, composite cell frame design provides reconfigured, permanently sealed coolant cavities as shown in Figure 12. This design has several advantages:

- Firstly, in contrast with the current baseline cell, the present coolant cavity design will significantly improve thermal conduction from the cathode, where most of the heat is produced; the thickness of plastic between it and the coolant will be minimized. Cell temperature regulation will therefore improve. Conversely, the new design reduces thermal conduction from the anode, where water is produced (see Figure 2); a thermally conducting metallic sheet (current collector) between anode and coolant is replaced by a thickness of insulating plastic and a foil current collector. This will provide desirably higher anode temperatures. The net effect will be to provide improved cooling and temperature regulation at the primary point of heat production and promote water removal at the point of water production.

- Secondly, when cell operation ceases, the anode temperature will drop to the coolant temperature at the same time water production stops, and cell dryout will be avoided. (Conversely, the coolant temperature will not be so low as to permit flooding). In particular, this will avoid damage (e.g., by crossover) to cells that are electrically isolated by the in situ cell maintenance technique (see Technology Advancement Studies chapter).

- Thirdly, the bonded cavity seal will be more reliable than the prior mechanical (O-ring) seal.

- Fourthly, the coolant will intrinsically be electrically insulated from the cell, thereby eliminating the need to electrically isolate coolant components.

The composite cell frame design incorporates silver foil current collectors at both cathode and anode (previously the anode current collector was a 0.5 mm (0.020 in) thick nickel plate with attached fins). This will greatly reduce current collector weight (e.g., by a factor of ten) and eliminate exposed edges. Current connections to these foils will be made through standard commercial pin connectors of proven design.

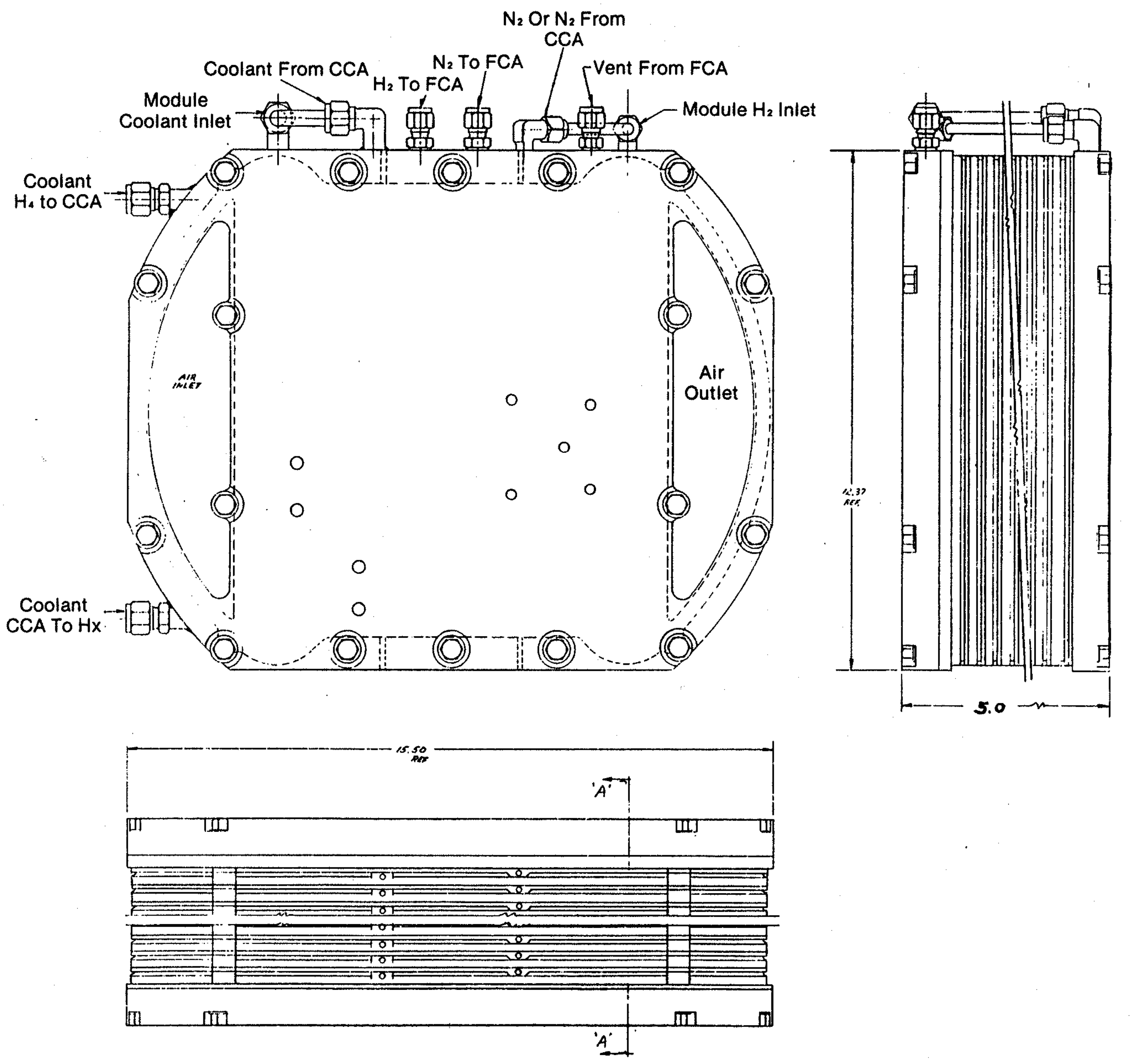


FIGURE 11 COMPOSITE CELL EDC MODULE FOR CS-1

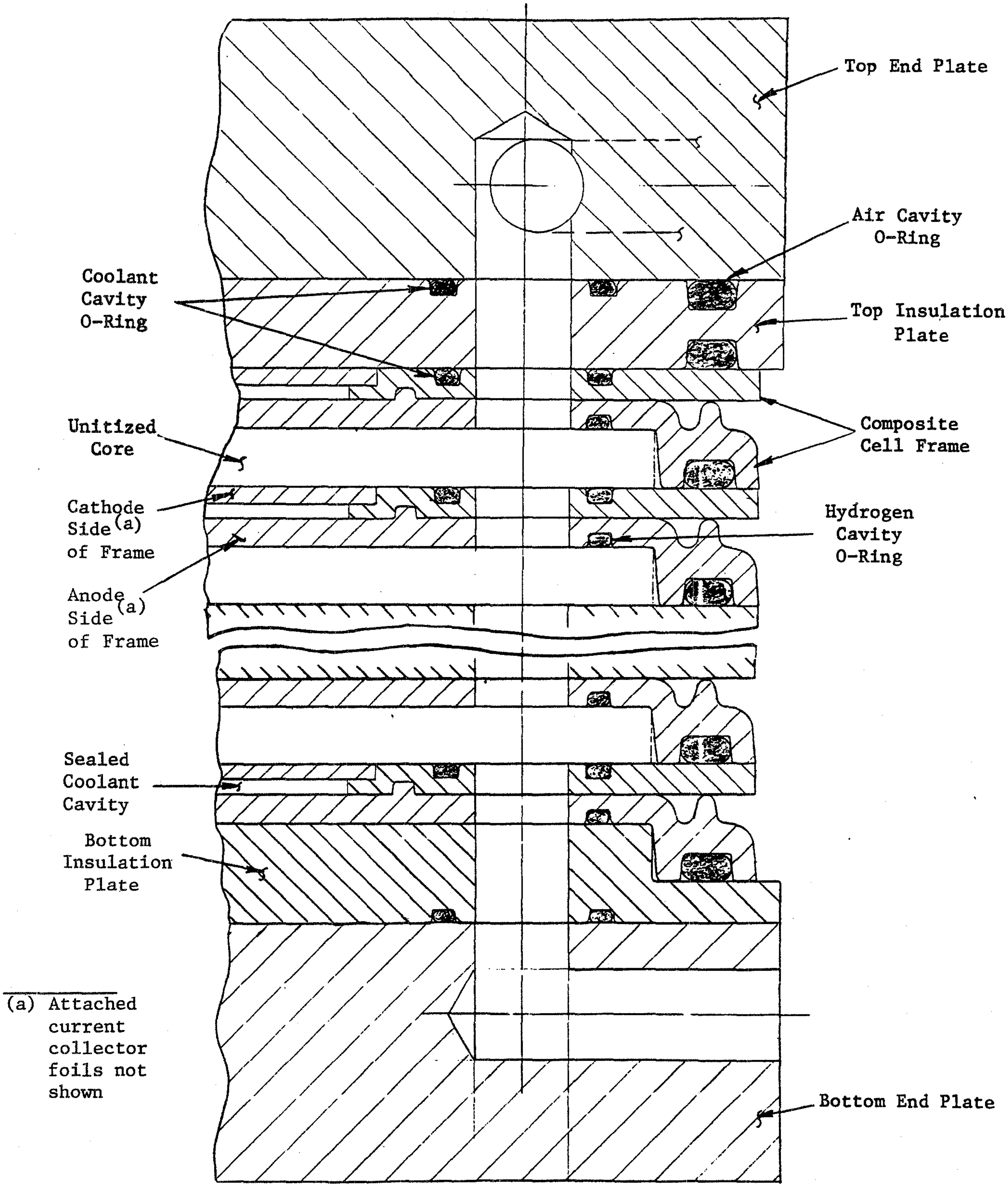


FIGURE 12 CROSS-SECTIONAL VIEW OF COMPOSITE CELL EDC MODULE

The molded feed cavities that distribute H_2 flow across the anode will be deepened. This will avoid significant H_2 pressure drops that can occur with large module stacks.

Finally, the cell frame design permits improved manufacturing techniques. The design will eliminate the precise tolerance machining steps previously required. It is also projected that injection molding scrap rates can be reduced.

Fluids Control Assembly

The CS-1 EDCM, like its precursors, will require monitoring and control of H_2 flow, H_2 backpressure and N_2 purge gas flow. These functions, previously performed by eleven discreet components, have now been integrated into a single lightweight, low volume FCA. The functions and advantages of this device are listed in Table 5.

An engineering prototype FCA has been designed, fabricated and tested. The characteristics and evaluation of this device are detailed in a separate chapter of this report.

Coolant Control Assembly

Three elements are essential to temperature control of a liquid cooled electrochemical module: a circulation pump, a diverter valve to regulate the proportion of module coolant flowing through and around a liquid/liquid heat exchanger (connected to a central coolant source) and a liquid/gas accumulator to accommodate module coolant expansion/contraction. These discrete components which require individual mounting and interconnecting plumbing, have been replaced by an integrated CCA. The advantages of this unit are listed in Table 6.

An engineering CCA has been designed, fabricated and tested. The characteristics and evaluation of this unit are described in a separate chapter of this report.

Current Controller

The current controller provides a regulated current sink for the power generated by the EDCM. It is packaged as a separate device. It is designed to be liquid cooled and located with the CS-1 mechanical assembly. The central coolant source that interfaces with the CCA will remove the waste heat from the current controller. Placement of the current controller near the EDCM will reduce the length of the electrical leads between the module and the current controller and thereby minimize voltage drops. Eliminating heavy leads from the C/M I enclosure to the module will result in significant savings in weight and size.

Control/Monitor Instrumentation

The function of the C/M I is to provide for automatic mode and mode transition control, automatic shutdown for self-protection, monitoring of subsystem parameters and interfacing with ground test instrumentation and data acquisition facilities.

TABLE 5 FLUIDS CONTROL ASSEMBLY

Functions

- To control and monitor H_2 flow
- To control and monitor N_2 purge flow
- To maintain and monitor anode gas backpressure
- To enable automatic configuration of fluid passages

Decrease in Size, Weight, Power, Complexity

Size Factor	% Reduction	From	To
• No. of Components	91	11	1
• No. of Connections	69	16	5
• Weight, kg (lb)	64	5 (11)	<2 (<4)
• Volume, cm^3 (in^3)	71	6884 (420)	1967 (120)
• Power, W	75	80	20

Other Major Benefits

- Subsystem simplification for user acceptance
- Ease of in-flight maintenance (1 Line Replaceable Unit (LRU) with 3 Line Replaceable Components (LRC's))
- Applicable wherever EDC technology is employed

TABLE 6 COOLANT CONTROL ASSEMBLY

Functions

- To maintain constant coolant flow rate to the EDCM
- To vary coolant temperature

Decrease in Size, Weight, Power, Complexity

Size Factor	% Reduction	From	To
• No. of Components	67	3	1
• No. of Connections	43	7	4
• Weight, kg (lb)	26	5.7 (12.5)	4.2 (9.3)
• Volume, cm^3 (in^3)	56	8851 (540)	3934 (240)
• Power, W	37	137	86

Other Major Benefits

- Subsystem simplification for user acceptance
- Ease of in-flight maintenance (1 LRU with 2 LRC's)
- Applicable as common Advanced Life Support System (ALSS) component

The design version of the C/M I was based on the Life Systems' minicomputer-based Series 100 systems. These provide for flexible operator interfaces with subsystem operation. The front panel of this unit is depicted in Figure 13. A similar C/M I, previously developed for a three-person CO_2 collection subsystem is depicted in Figure 14. A block diagram for the CS-1 C/M I is shown in Figure 15, and design characteristics are listed in Table 7.

Due to advances in parallel technology (Contract NAS2-10674) it is projected that a System 200 Series C/M I, a much smaller, flight version preprototype will actually be built if the corresponding CS-1 contract is issued. However, the control features will be analogous to those discussed below for the Series 100, except for the flexible front panel interfaces. This C/M I is projected to weigh 16 kg (35 lb), occupy 0.28 m^3 (1.0 ft^3) and consume 50 W of power.

General Description

The C/M I receives signals from or transmits signals to the M/EA sensors and actuators. Through these it controls and monitors subsystem pressures, flow rates, temperatures, voltages, currents and valve positions in each operating mode (shown in Figure 6 and described in Table 2). It implements each mode as initiated automatically or manually and provides fail-safe operational changes to protect the subsystem if malfunctions occur.

Internally, process operating mode control is a relatively complex operation. It includes selection of different unit processes, selection of valve positions, sequencing of valve positions, sequencing of actuators and checking parametric conditions as the transition proceeds. However, this procedure for control is fully automated by the C/M I so that the operator only needs to press the Mode Change request buttons to initiate transition sequences.

The hardware and software design permits real-time communication between the operator and the mechanical subsystem. On the operator/subsystem interface side, the C/M I provides the operator a front panel with a keyboard designed to accept operator commands and display subsystem messages. On the process side an analog and digital interface board is used for communication between the minicomputer and the sensors and actuators of the subsystem. A static trend analysis is included that compares parameter readings with setpoints that indicate Caution, Warning and Alarm thresholds. Visual displays indicating whether a parameter is in the Normal, Caution, Warning or Alarm range are provided on the front panel.

Software

The software manages the entire operation of the C/M I as shown in Figure 16. Each of the major elements is listed below.

a. Power-Failure Control (PFC)
b. Real-Time Executive (RTE)
c. Front Panel Command Handler
d. Operating Mode Control
e. Mode Transition Control
f. Process Parameter Control

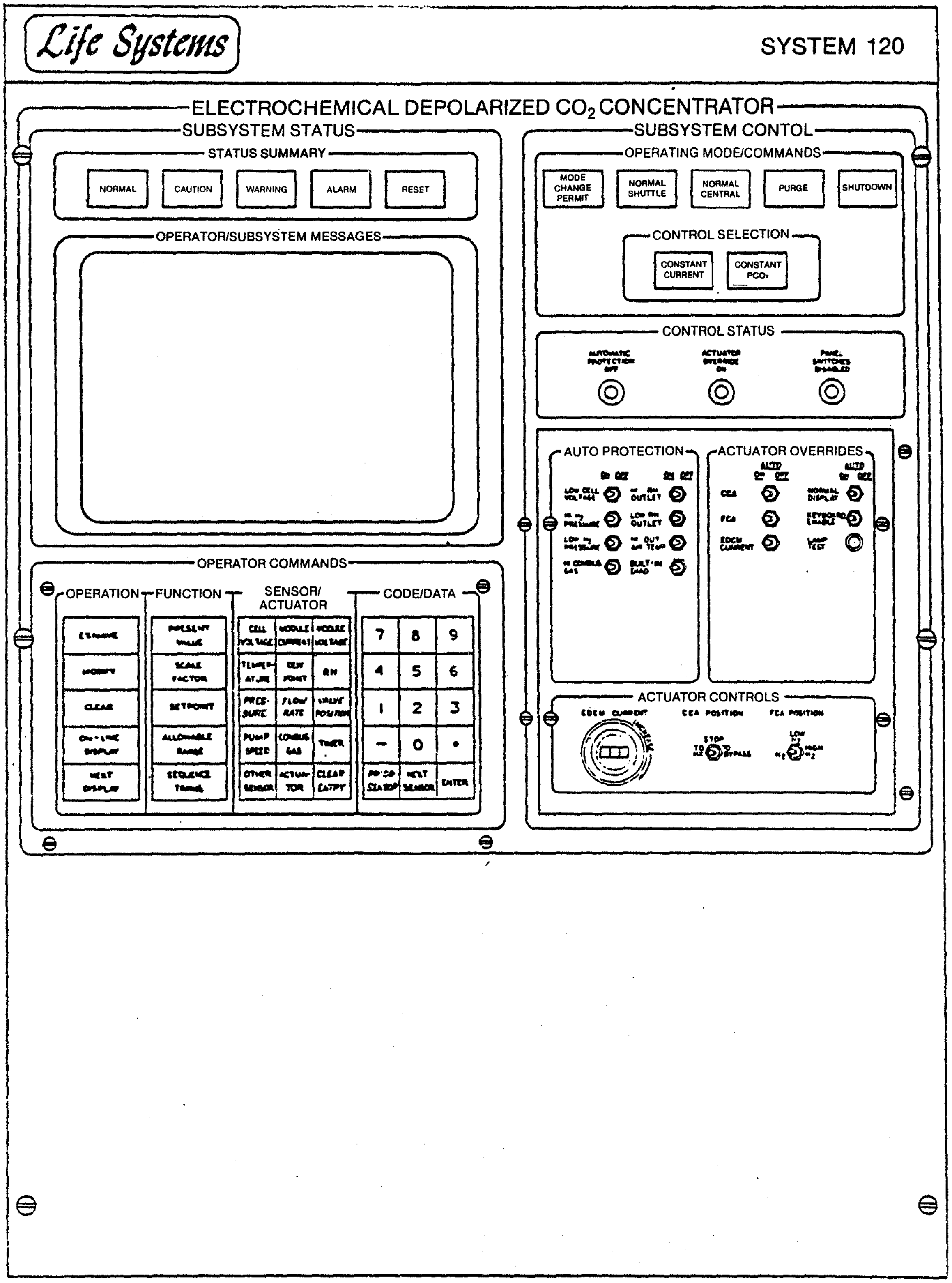


FIGURE 13 CS-1 OPERATOR/SUBSYSTEM INTERFACE PANEL

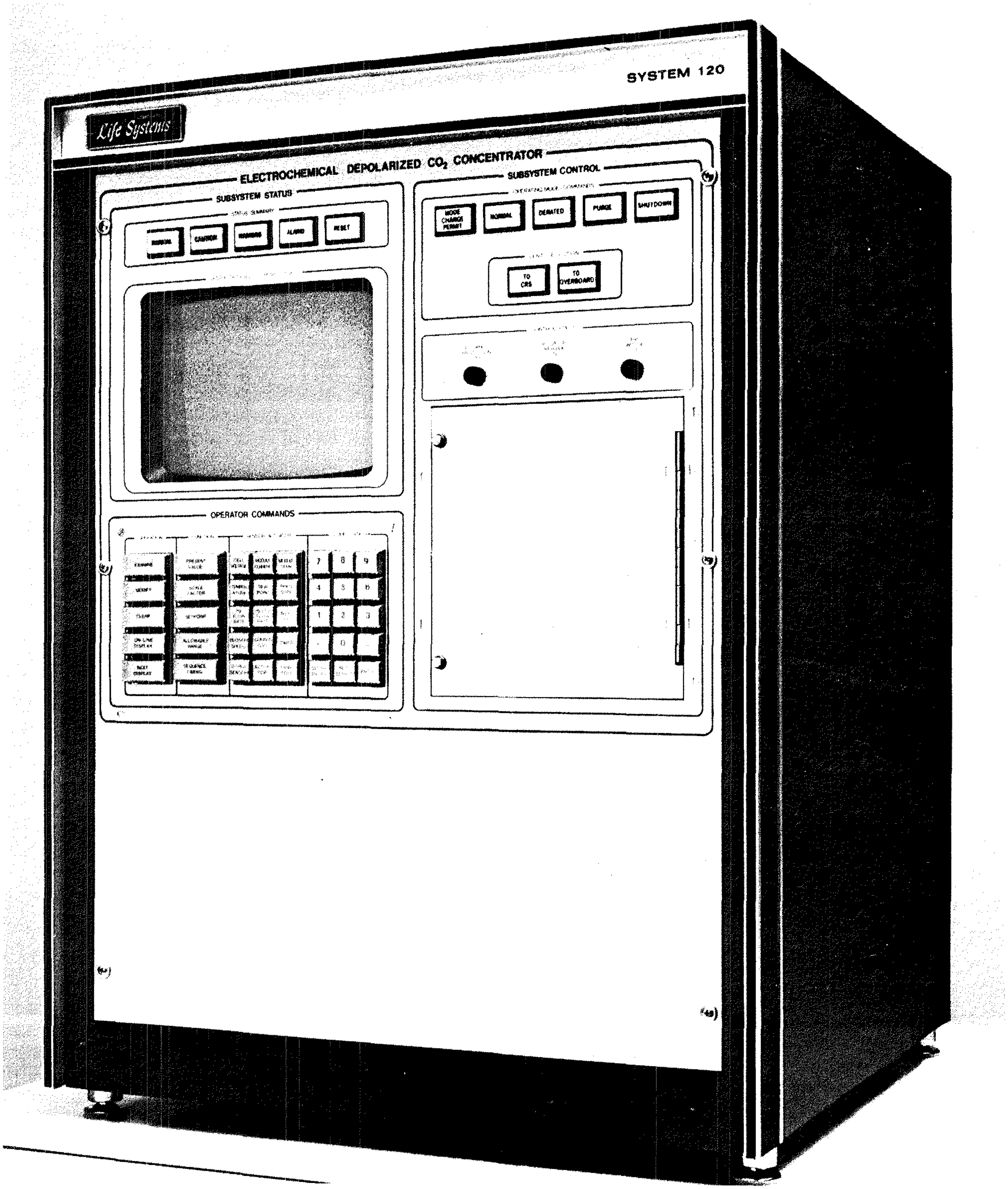


FIGURE 14 DEVELOPMENTAL CONTROL/MONITOR INSTRUMENTATION

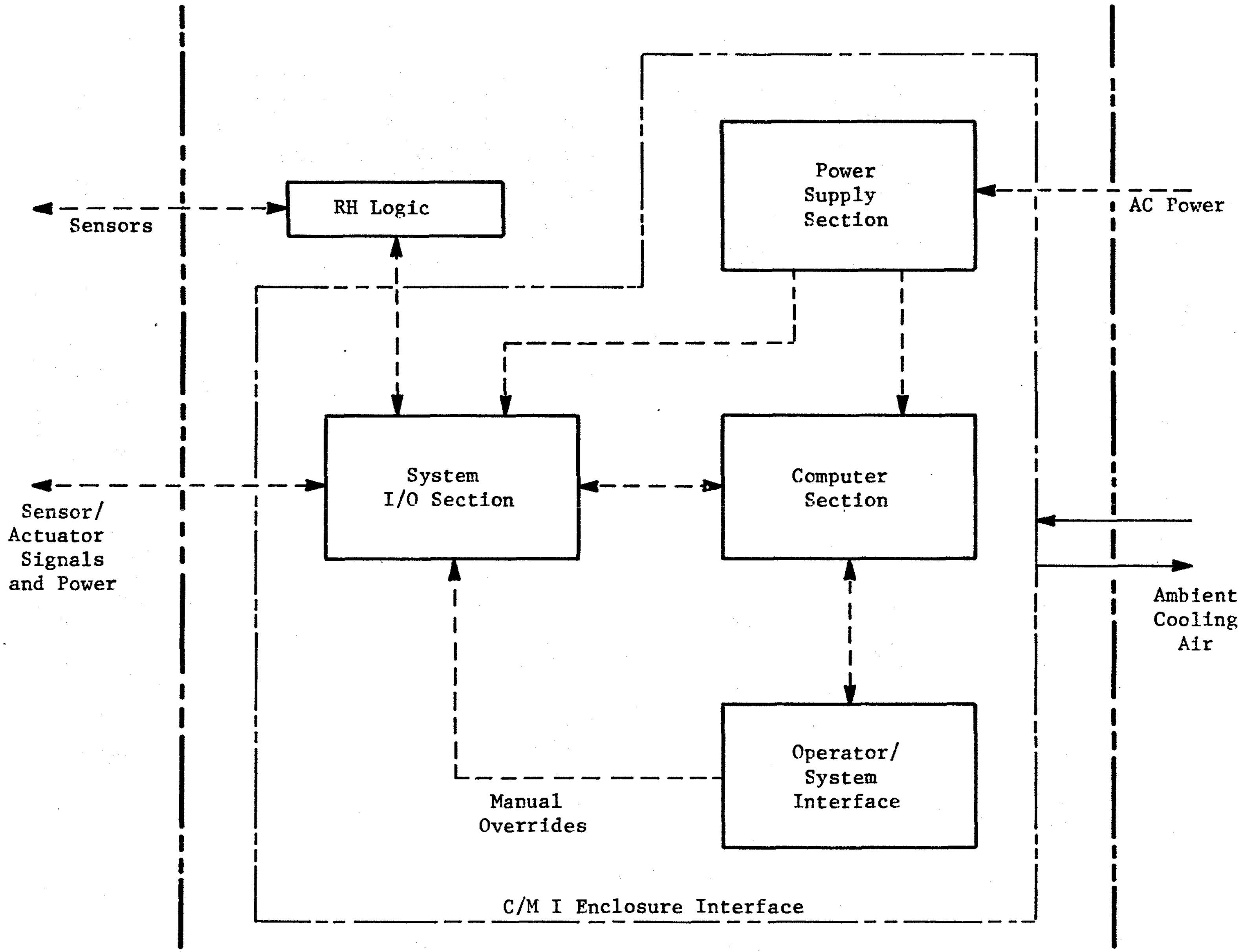


FIGURE 15 CS-1 C/M I HARDWARE FUNCTIONAL BLOCK DIAGRAM

TABLE 7 CS-1 CONTROL/MONITOR INSTRUMENTATION DESIGN CHARACTERISTICS

Dimensions (D x W x H), cm (in)	53.3 x 53.3 x 71.3 (21 x 21 x 28.6)
Weight, kg (lb)	102 (225)
Power Input, W	712
Power Consumption, W	522
Line Voltage, V	115, 1Ø
Line Frequency, Hz	400 and 60
Input Sensor Signal Range, VDC	0 to 5
Output Actuator Signal Range, VDC	0 to 5
Processor	
Type of Computer	CAI LSI-2/20 Minicomputer
Word Size, Bits	16
Memory Size, K Words of Core	16
Memory Speed, ns	1200
Instruction Cycle Time, ns	150
I/O Transfer Rate, Megawords/s	1.67
Other Important Features	• Real Time Clock • DMA Channels • Hardware Multiply/Divide • Stack Processing • Automatic and Blocked I/O • Power Fail Restart
Input/Output	
Number of Analog Inputs	31
Number of Analog Outputs	1
Number of Digital Inputs	12
Number of Digital Outputs	7
Front Panel	
Command Inputs	Pushbutton Switches
Message Display	Color-Coded Indicators and CRT Display
Display CRT Capacity, Characters	1,920 (80 x 24)
Number of Manual Overrides	4
Operating Modes	
Number of Operating Modes	4
Number of Allowable Mode Transitions	9[a]
Number of Normal Mode Control Methods	2

(a) Mode IB capability only.

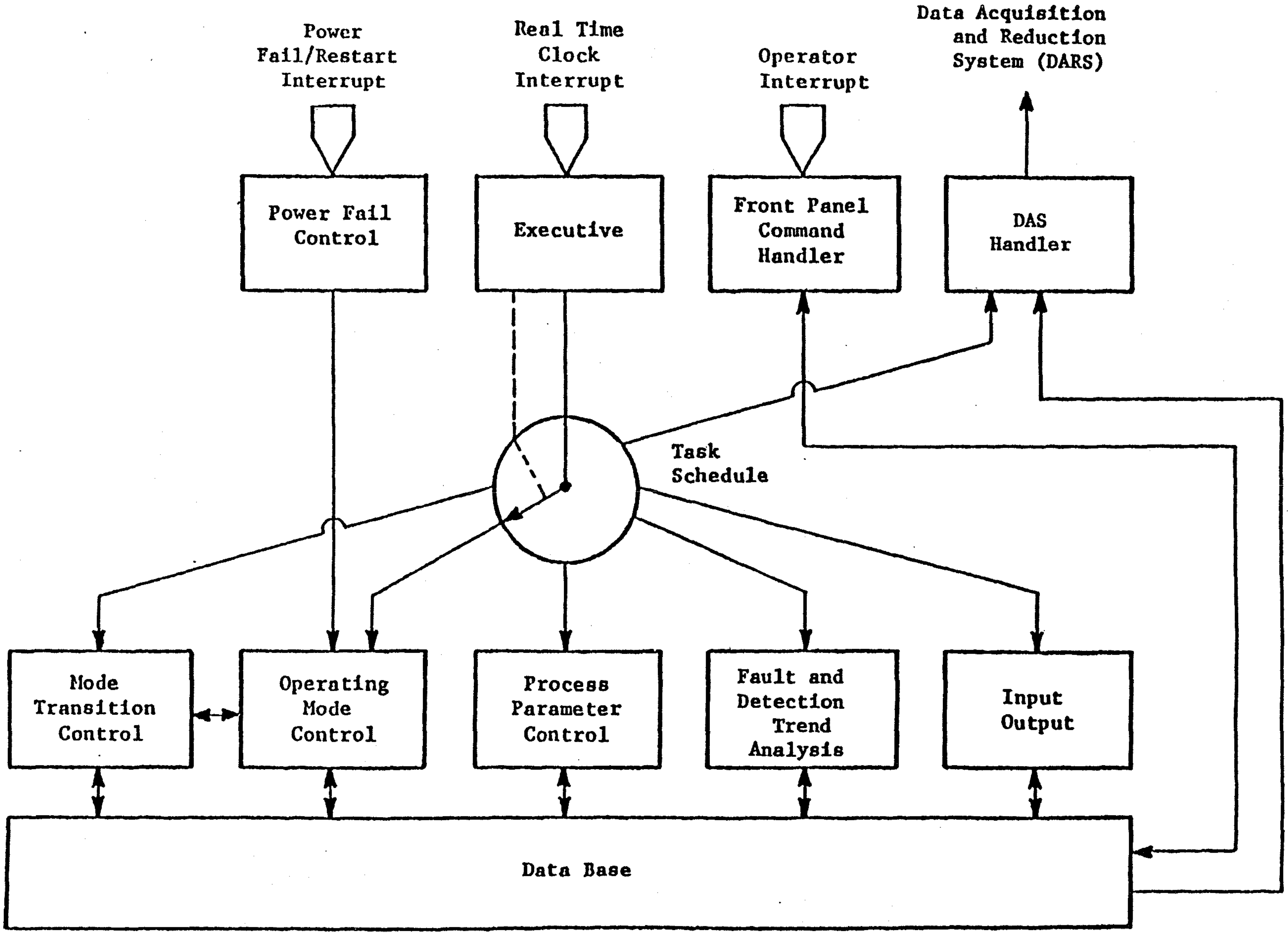


FIGURE 16 CS-1 C/M I SOFTWARE BLOCK DIAGRAM

g. Fault Detection and Trend Analysis
h. Input/Output (I/O)
i. Data Acquisition System (DAS) Handler

The items are discussed in more detail as follows.

a. Power-Failure Control

The PFC resets the system conditions when power is applied to the C/M I.

b. Real-Time Executive

The RTE is the heart and "chief executive" of the software. It is driven by the real-time clock (a hardware function) and is designed to execute different programs in a timely fashion.

c. Front Panel Command Handler

The Front Panel Command Handler allows the operator to communicate with the subsystem through the front panel buttons.

d. Operating Mode Control

Operating mode control is designed to resolve all mode change requests in this system. Whenever power is first applied to the C/M I, the computer will go through the startup procedure as programmed in the power failure control module such that the C/M I is in Shutdown mode when completed. Any mode change requests, either manually generated or subsystem generated, will be checked by the operating mode control module.

e. Mode Transition Control

Mode transition control modules provide the necessary transition sequences from one operating mode to another.

f. Process Parameter Control

The process parameter control and monitor routines are designed specifically for the CS-1 and are controlled by the RTE to maintain the parameters within the specified ranges. The type of controls include:

1. Open-loop programmed control
2. Feedback on/off control
3. Supervisory control
4. Feedback proportional control
5. Feedback proportional, integral and differential (PID) control

g. Fault Detection and Trend Analysis

One of the most important requirements of the C/M I is the protection of equipment and operator. The instrumentation has been designed to be capable of detecting symptoms of component failures. In order to detect the symptoms, sensors have been incorporated to monitor the key parameters of the subsystem. When a parameter reaches a certain limit, the subsystem will be shut down to prevent damages. Normal, Caution, Warning and Alarm indicators are provided on the front panel.

h. Input/Output

The I/O modules will be under RTE control. The input routine will read all data from the Analog to Digital Converter (ADC) channels and put them into the input buffer. The output routine will transfer all the data in the output buffer to the output channels of the digital (I/O) interface. Each analog input has a 12-bit resolution and occupies 2 bytes in the buffer.

i. DAS Handler

The DAS Handler provides for external communication with a Data Acquisition and Reduction System (DARS) for monitoring of process variables.

Test Support Accessories

Figure 17 illustrates the integrated CS-1 and TSA components and Figure 18 illustrates the projected laboratory arrangement of the CS-1 and the TSA. The TSA supplies process fluids, electrical power, coolant interfaces, precise control of certain operating parameters and monitoring of CO_2 removal and power output performance. It is capable of varying process air flow rate, temperature and composition (pCO_2 and RH), and H_2 pressure, flow rate and RH. The TSA is also equipped with automatic secondary shutdown protection for over-temperature, excessive H_2 pressure, and low cell voltages to protect the CS-1 subsystem during unattended operation. The TSA includes anode gas analysis using an infrared analysis for pCO_2, a hygrometer for dew point measurement (RH), two flow meters for gas and air flow rates, and standard electronic meters for temperature, voltage and current readouts.

Some CS-1 TSA was assembled under the subject contract. Future CS-1 subsystem development and testing efforts are projected to include minor modifications to this TSA and debug, checkout and shutdown testing.

UNITIZED CORE ELECTROCHEMICAL CELL DEVELOPMENT

The objectives of the unitized core development were to achieve reproducible and predictable high level EDC performance over extended ranges of differential cell pressure and process air RH.

The unitized core concept enables such improvements by providing permanently bonded, versus mechanically sealed, cell construction. This technology prevents gas leakage across the edges of the cell matrix and therefore permits

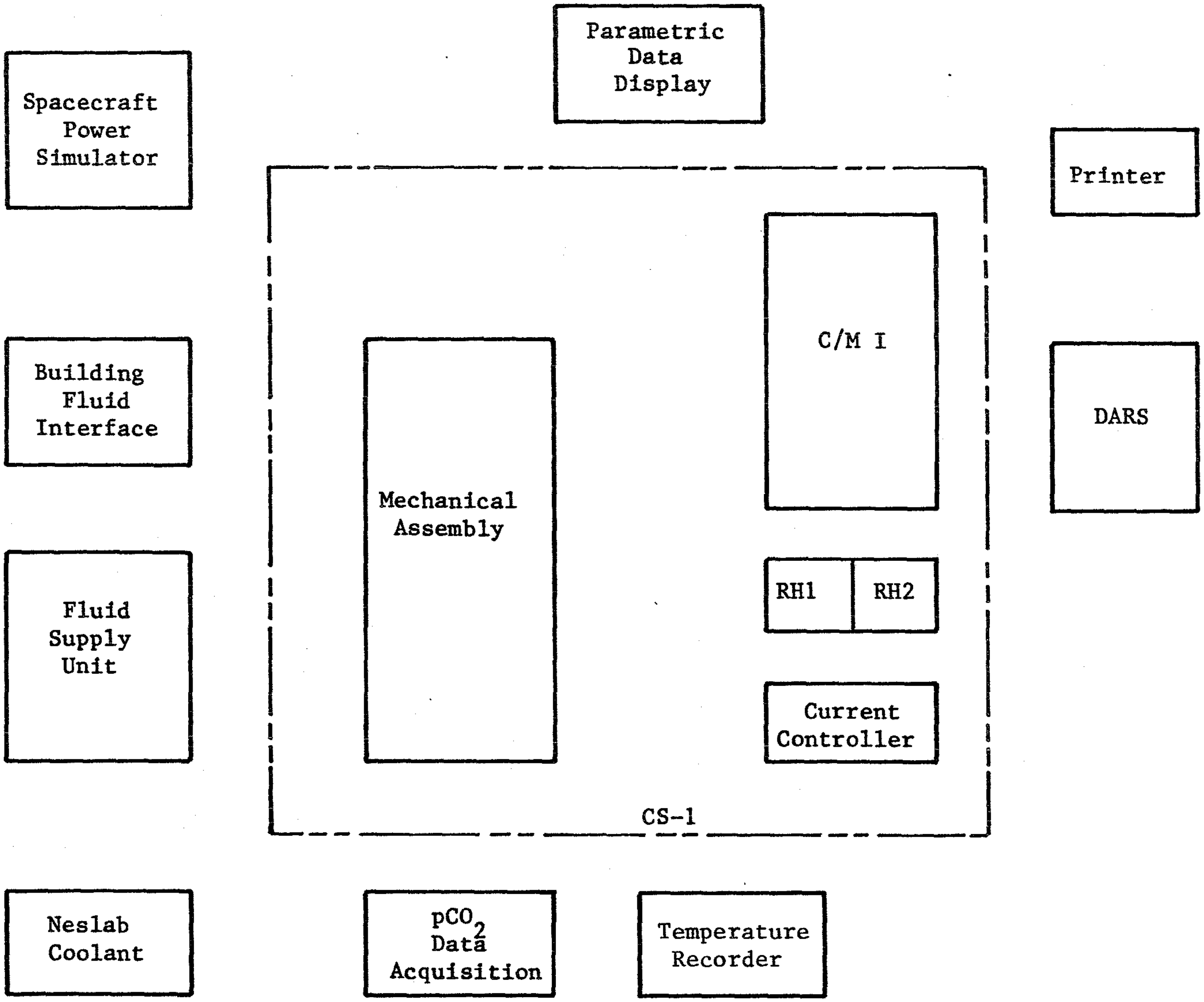


FIGURE 17 INTEGRATED CS-1 AND TSA COMPONENTS AND ASSEMBLIES

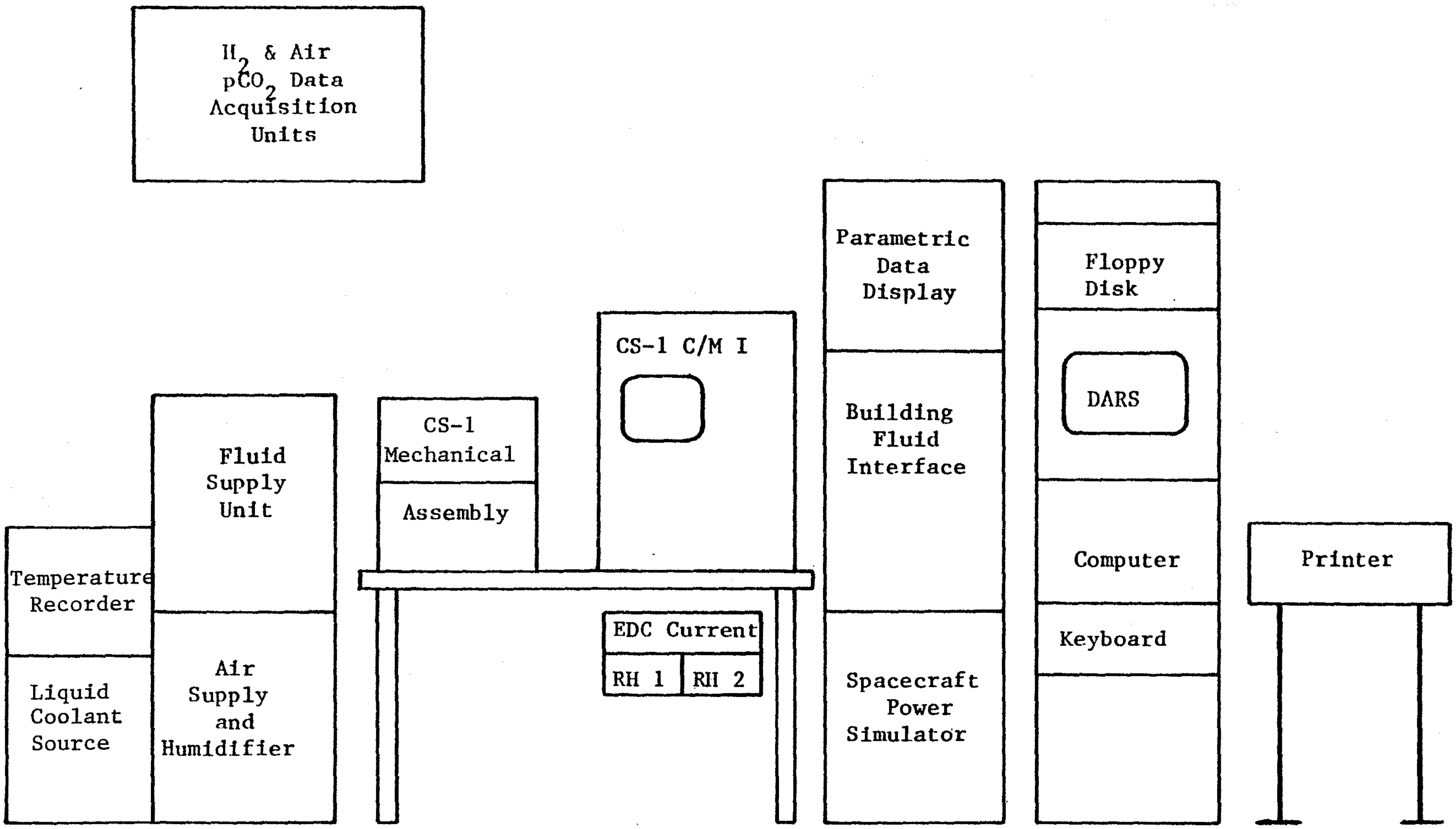


FIGURE 18 CS-1 AND TSA PACKAGING (AS IN LAB)

operation at higher H_2/air differential pressures. It also provides uniform matrix support and thickness both up to and including the edges, resulting in uniform electrolyte distribution and a superior RH tolerance range. The following subsections describe the development and evaluation of the unitized core, composite cell technology at the breadboard, single cell and modular levels, as well as the development of a special test stand for module evaluation.

Core Design

Since a major driver for composite EDC cell construction was to enhance pressure differential and broad RH capabilities, primary emphasis was directed toward selection of compatible materials and the fabrication concept for the unitized core, the heart of the cell. Following materials selection, preliminary methodology and equipment were defined for fabricating the building blocks of the unitized core (framed matrix, framed gas cavity spacers and electrodes)and assembly of the core. An initial set of fabrication procedures was then written, and fixtures were fabricated to allow building of a breadboard 7.6 x 7.6 cm (3 x 3 in) cell. Following an iterative process of procedure improvements, a unitized core for this cell was successfully fabricated. Analogous procedures were developed for full size, 4.6 dm^2 (0.5 ft^2) cells.

The unitized core concept is illustrated in Figure 19. The unitized core combines the five major elements of the electrochemical cell: (1) process air gas cavity spacer, (2) the cathode, (3) the cell matrix with edge frame and edge sealing provisions, (4) the anode, and (5) the process H_2 gas cavity spacer.

The overall concept of the composite EDC cell design is illustrated in Figure 20. The composite cell consists of the unitized core, an injection-molded polysulfone plastic frame for manifolding and distributing process gases and internal liquid coolant and current collectors for delivering current to the cell. The composite cell polysulfone cell frame is fabricated in two sections, cemented together after fabrication to provide an isolated internal liquid coolant cavity for the EDC cell. Both anode and cathode current collectors are silver foils bonded to the cell frames. Process fluid isolation is accomplished by an arrangement of O-rings that provide seals between each composite cell in a module stack, as was shown in Figure 12. (In the development cells discussed in this chapter, unitized cores were cemented into modified baseline cell frames rather than being sealed to the frames with an O-ring, as in the advanced CS-1 design.)

Core Fabrication Technique

Fabrication of a unitized core involves, firstly, the application of epoxy rims around the perimeters of the process gas cavity spacers and the cell matrix (middle of Figure 19). These subassemblies are then combined with the electrodes to form the unitized core using more epoxy (right side of Figure 19). This approach provides a uniform support of the cell matrix over its entire area, versus edge distortion, thereby providing maximum gas pressure sealing characteristics of the electrochemical cell and uniform response of the electrolyte to humidity changes.

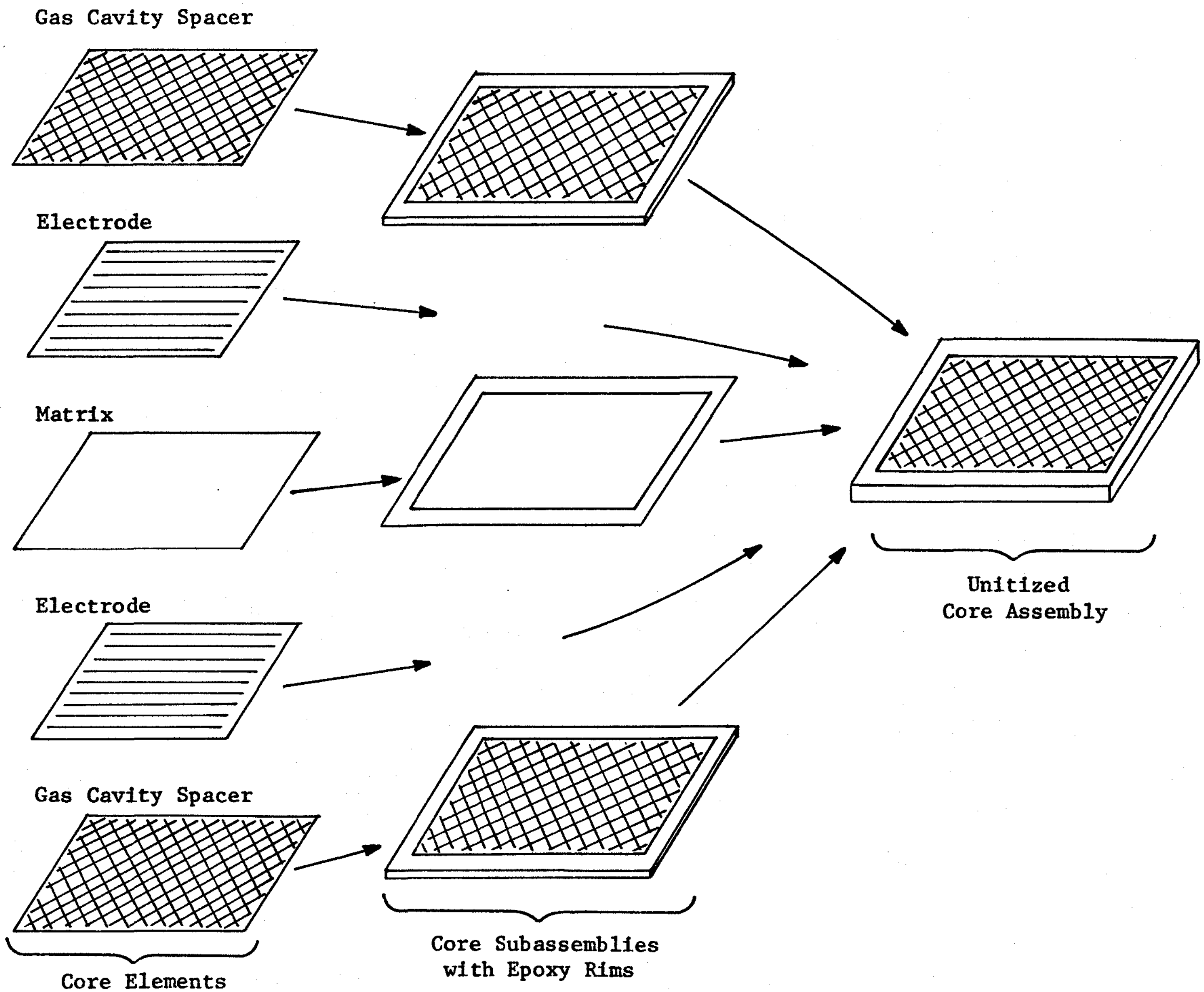


FIGURE 19 UNITIZED CORE CONCEPT FOR EDC COMPOSITE CELL

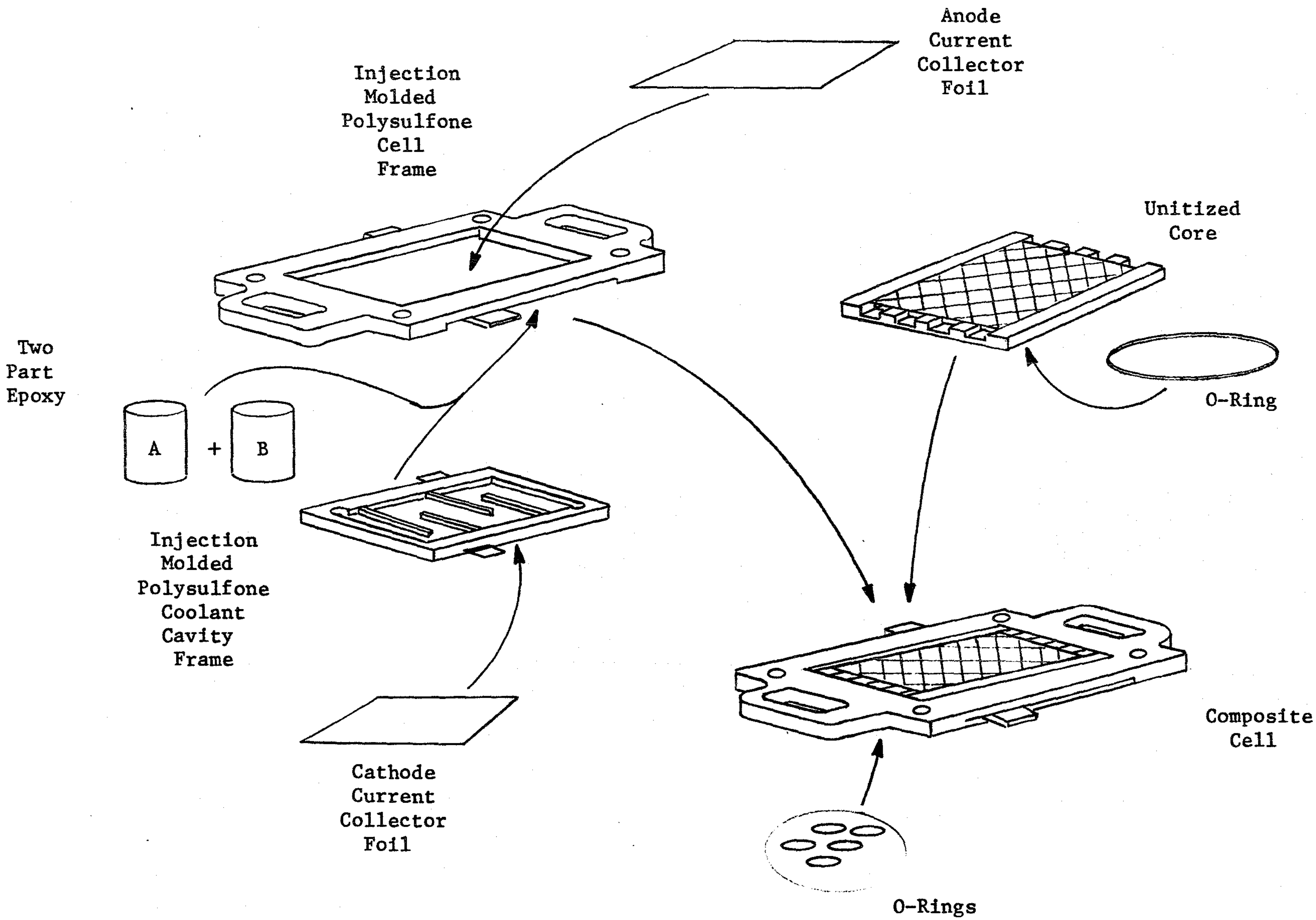


FIGURE 20 COMPOSITE EDC CELL CONCEPT

The key structural material selected for the unitized core fabrication is an epoxy resin. It is used to form the frames around the matrix and the expanded metal cavity spacers and to provide final sealing of the various building blocks to form a unitized core. The combination of a literature search and laboratory experiments resulted in the selection of 3M Corporation's Epoxy Number 2216 (A&B). This material is compatible with the environment, exhibits sufficient strength and also has the desired flexibility needed. Critical points in the fabrication process include maintaining proper epoxy width, thickness and uniformity (absence of air bubbles and pockets in the cured epoxy rim). These parameters are controlled using varied, combined applications of heat, pressure, and vacuum. Care must be taken to ensure that all components of the core are properly aligned with respect to gas inlet and outlet areas, that the cell matrix and electrode active areas are free from epoxy, and that an effective epoxy seal is achieved around the edge of the unitized core.

Small Scale Single Cell Development

The initial development and testing of unitized core technology was performed on a reduced scale with simplified, air-cooled (versus liquid-cooled) cell hardware. The elements for two 7.6 x 7.6 cm (3 x 3 in) (outside edge dimensions) unitized cores were fabricated and then assembled using the techniques described above. The first core utilized a Johns-Manville fuel cell-grade white asbestos matrix. The second incorporated the LSI-fabricated reconstituted white asbestos matrix.

Results of the gas pressure breakthrough testing are provided in Table 8. Both cores exhibited exceptionally high gas breakthrough pressures, especially the one incorporating the LSI reconstituted white asbestos matrix (827 to 1034 kPa (120 to 150 psid)). These results are a direct indication of the uniform support provided to the cell matrix in the unitized core.

The two "3 x 3 cores" were also tested for CO_2 removal performance versus time, H_2 backpressure and inlet air RH. Initially, the core containing the Johns-Manville matrix was operated for a total of 254 hours. The cell performance results are provided in Figure 21. Successful operation was demonstrated at three levels of H_2 backpressure: 35, 69 and 103 kPa (5, 10 and 15 psid).

The results of 750 hours of testing the core containing the LSI matrix are provided in Figure 22. (The baseline operating conditions and the significance of the "balloons" are the same as those defined in Figure 21.) The constant H_2 backpressure was 35 kPa (5 psid). Improved CO_2 removal efficiency and operating cell voltage were observed relative to the performance of the initial 3 x 3 unitized core. Acceptable performance was obtained even at low RH values. The improved performance was related to two features that upgraded the design of the second core. Firstly, the LSI reconstituted white asbestos matrix was used. This type of matrix had previously demonstrated greater H_2 backpressure, CO_2 removal and cell voltage performance than matrices cut from the Johns-Manville white asbestos. Secondly, a precise amount of electrode "bite" by the gas cavity spacer was incorporated during fabrication of the unitized core.

TABLE 8 UNITIZED CORE PRESSURE TEST RESULTS

	Core No. 1	Core No. 2
Electrodes	Baseline	Baseline
Matrix	JM White	LSI - White
Gas Cavity Spacer	Baseline	Baseline
Charge	56% LSI-D	56% LSI-D
Gas Breakthrough Pressure, kPa (psid)	520 (75)	830 to 1030 (120 to 150)
Reliable Operation Pressure, kPa (psid)	350 (50)	550 to 690 (80 to 100)

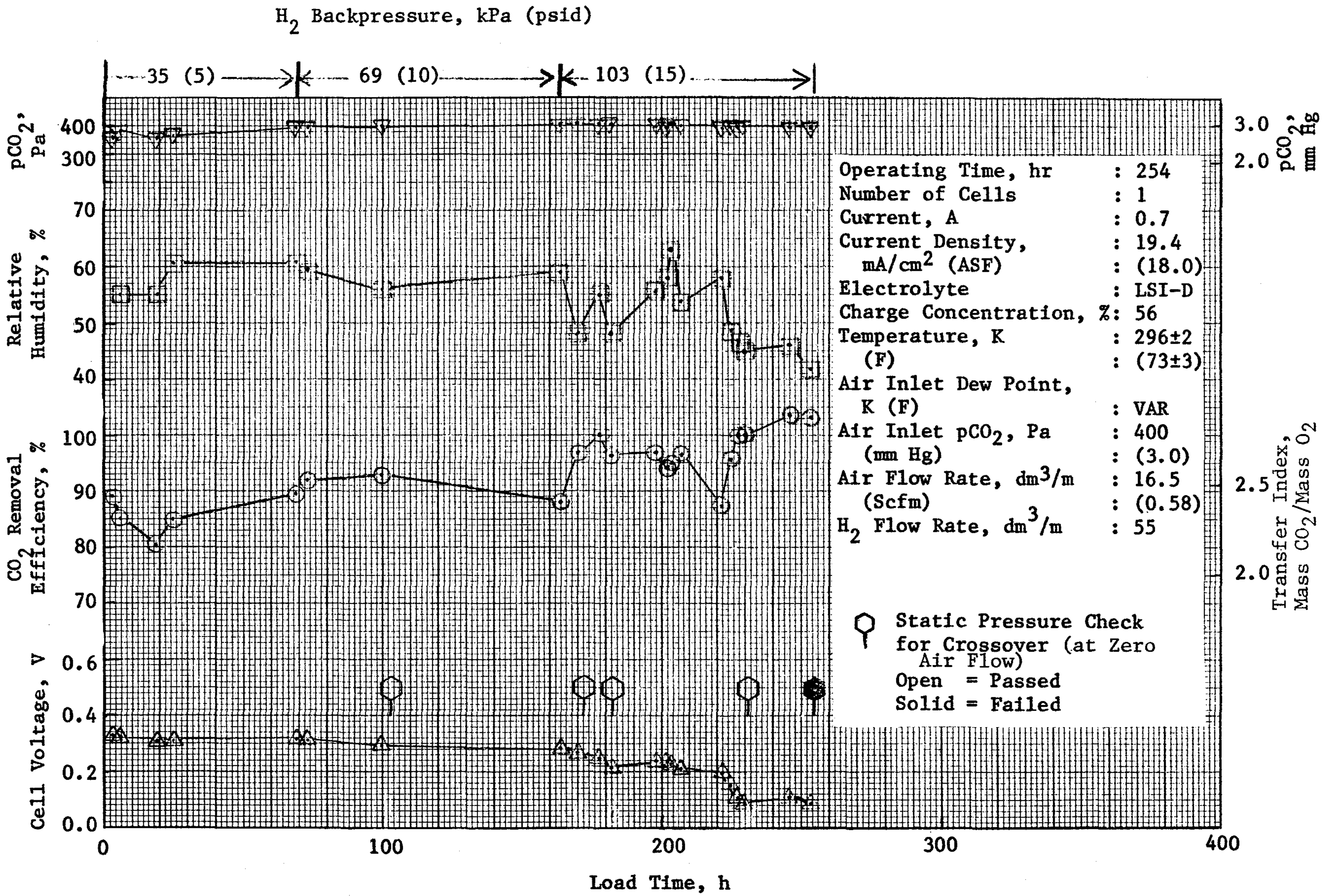


FIGURE 21 CELL PERFORMANCE OF UNITIZED CORE 3 x 3 IN WITH JM MATRIX

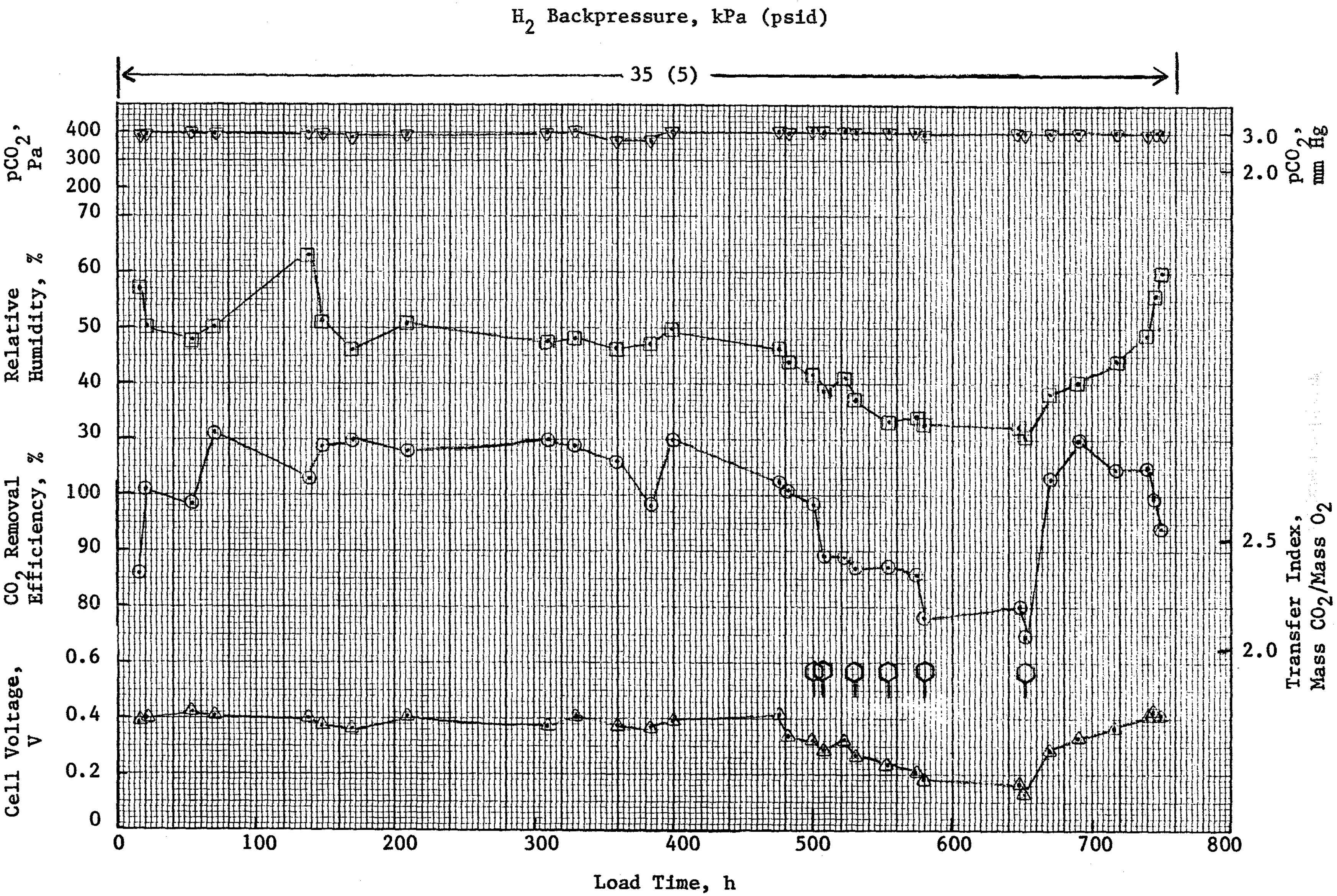


FIGURE 22 CELL PERFORMANCE OF UNITIZED CORE 3 x 3 IN WITH LSI MATRIX

Performance versus inlet RH is plotted in Figure 23 for the cell containing the LSI white asbestos matrix. This performance is compared with the technology goals (designated "B Level") of 1979-1980. The unitized core provided a wide operational RH range of 30 to 61%, five times that of a standard, compression sealed screen cell configuration (typically about 6%).

The average CO_2 removal efficiency of the second, improved cell was 100 to 110% and the average cell voltage was 0.4 V during the initial 400 hours of operation at an RH of 48 ± 4%. This exceptionally high CO_2 removal performance is associated with the high CO_2 mass flow rate per cell area, the unusually high process air mixing coefficient and the uniform operational RH that resulted from combining the process and cooling air through the unitized core process air cavity. This mode of operation was established to simplify cell hardware requirements for testing the "3 x 3 core." A cause of the somewhat low cell voltage could not be determined.

The successful pressure and performance testing of the unitized core confirmed the material selection and overall design approach for the concept.

Full Scale Single Cell Development

Development of unitized core, composite cell technology was subsequently extended to full scale, 4.6 dm^3 (0.5 ft^2) area cells. This technology was refined for single cells prior to fabrication of a complete (six-cell) module. One such cell is depicted component-wise in Figure 24.

Fabrication

The core fabrication methods were similar to those used for the breadboard "3 x 3 cores." The primary modification, other than scale-up, involved incorporation of a vacuum port into the pressing platen used to fabricate the cell matrix/epoxy trim. This minimized trapping of air around the edge of the matrix. However, the overall composite cells were fabricated using liquid-cooled baseline frames.

Three unitized core 4.6 dm^2 (0.5 ft^2) EDC cells were fabricated. The first and second unitized core assemblies (UC-001 and UC-002) incorporated previously used test electrodes. The third unitized core assembly (UC-003) incorporated a new electrode. The first two assemblies were used for H_2 cavity pressure differential testing and refinement of the unitized core fabrication technique. The final unitized core assembly was used for the one cell EDC shakedown and design verification testing.

Test Program

Checkout Test. All three unitized core EDC cells were checkout tested. Initially, the first unitized core cell (UC-001) was pressure checked for H_2 differential pressure capabilities. This cell maintained 27.6 kPa (4 lb/in^2) differential H_2 backpressure but failed to maintain greater pressures. The fabrication procedure was therefore slightly modified, and the second cell (UC-002) was fabricated and pressure tested. Excellent H_2 cavity pressure capabilities were demonstrated for this cell, as shown in Table 9. The differential breakthrough pressure was 965 kPa (140 lb/in^2). Finally, the third

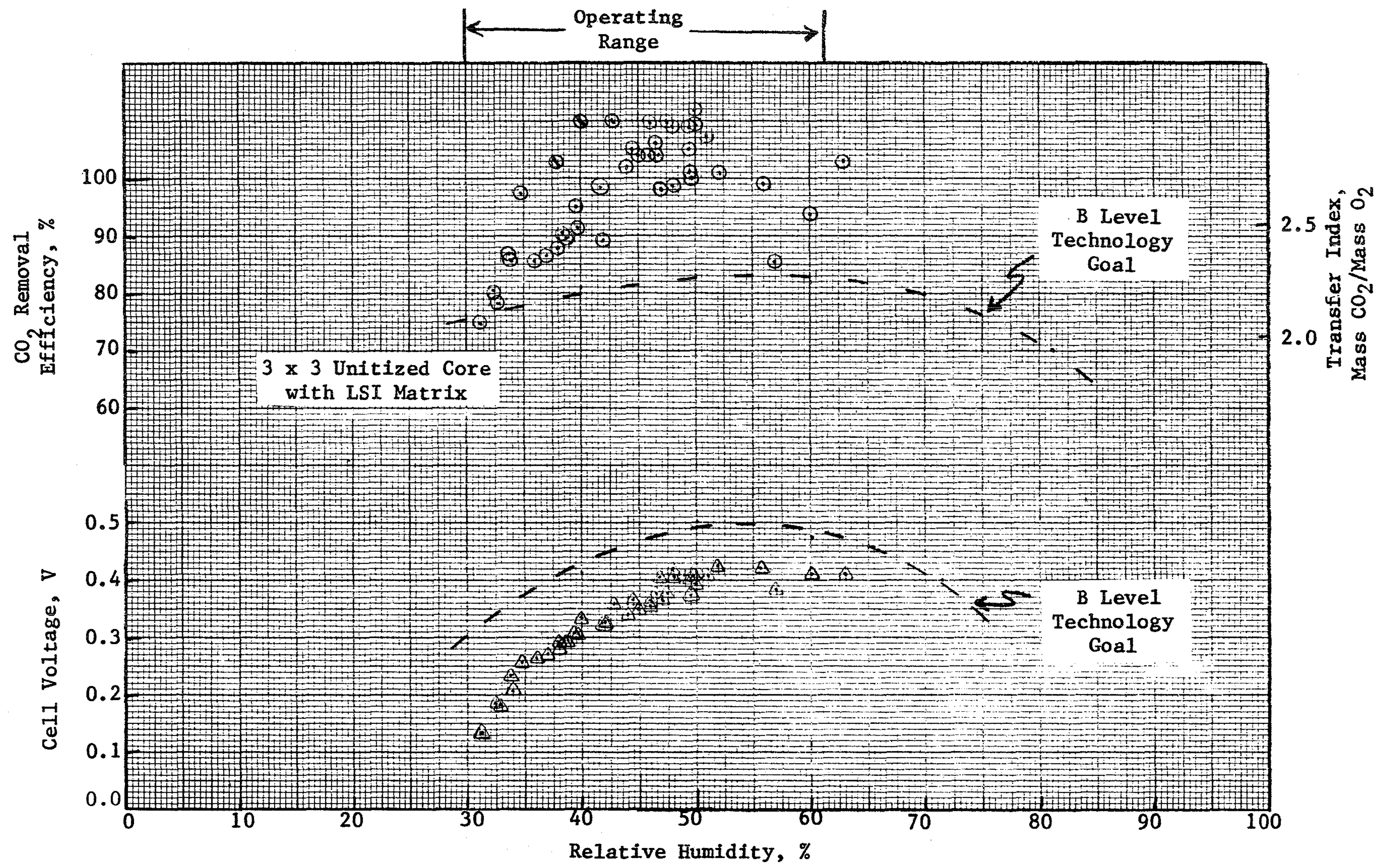


FIGURE 23 UNITIZED CORE PERFORMANCE AS A FUNCTION OF RELATIVE HUMIDITY

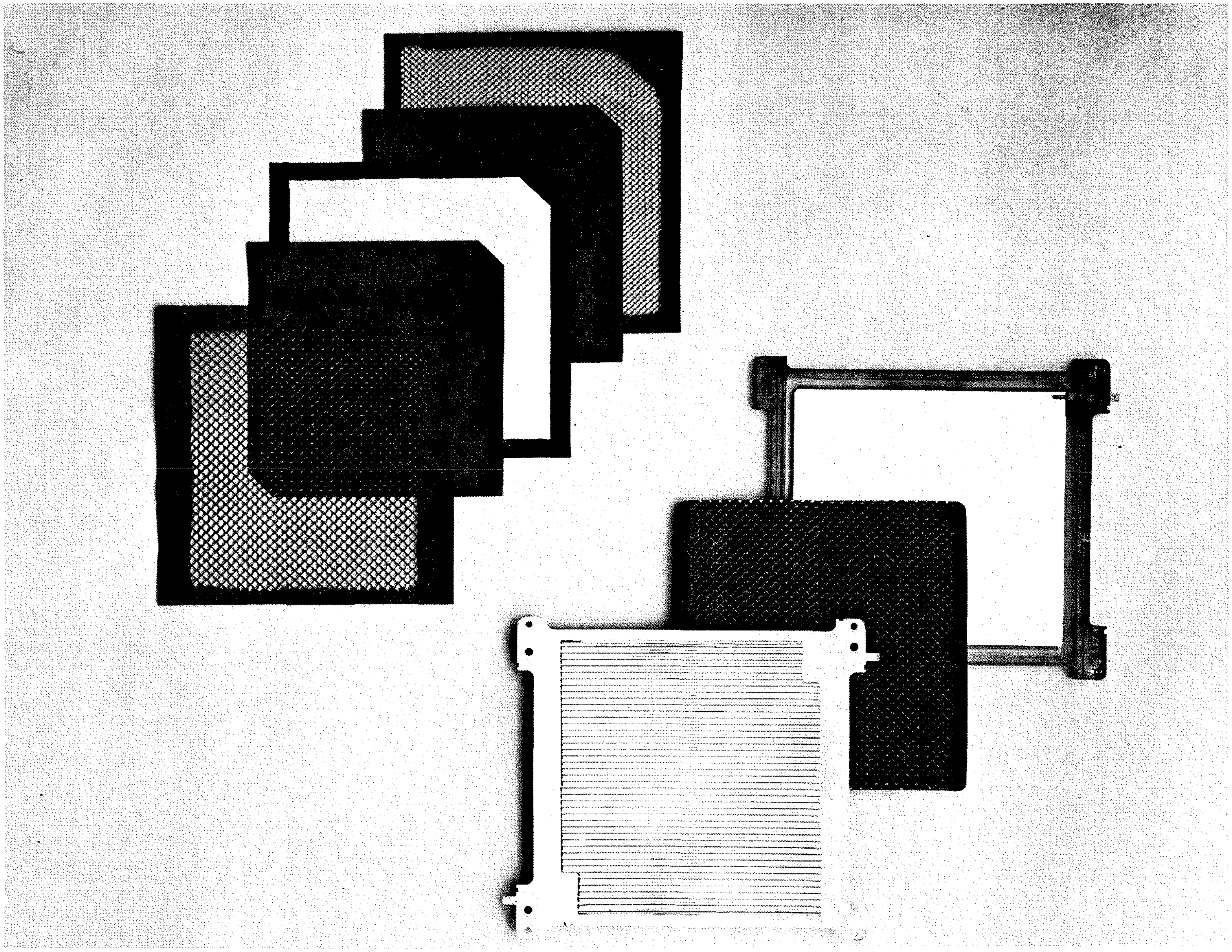


FIGURE 24 COMPONENTS VIEW OF UNITIZED CORE/COMPOSITE CELL

TABLE 9 PRESSURE TEST RESULTS FOR 4.6 dm^2 (0.5 ft^2) UNITIZED CORE INCORPORATED INTO AN ADVANCED EDC CELL FRAME[(a)]

Test No.	Test Description	Pressure, kPa (psid)	Comments
1	Static Pressure Check for 24 h at maximum pressure requirement for EDC cells	103 (15)	• No Leakage • No Bubbles Through Matrix
2	Static Pressure Check for 20 h	172 (25)	• No Bubbles Through Matrix • Leakage Rate of 2.1 kPa/h (0.31 psi/h)
3	Static Pressure Checks for 1 h	276 (40)	• No Bubbles Through Matrix • Leakage Rate of 9.6 kPa/h (1.4 psi/h) Observed Out of Cell Frame Current Tabs and H_2 O-ring Seals
4	Short Term Pressure Checks less than 10 min	414 (60)	• No Bubbles Through Matrix • Observed Leakage at Epoxy Seal between Unitized Core and Cell Frame
5	Matrix Breakthrough Pressure Test	965 (140)	• Observed First Bubbles Through Matrix

(a) Unitized Core (UC-002); 56% LSI-D Charge Concentration

cell (UC-003) was fabricated and pressure checked. No leakage was observed at 103 kPa (15 psid) differential pressure (the selected upper pressure test limit for cells to be performance tested). Cell UC-003 was then integrated with the test stand and shakedown and design verification testing were initiated.

Shakedown Test. Initially a pCO_2 span was performed on the UC-003 single cell EDCM. The results are plotted in Figure 25. Exceptionally high CO_2 removal efficiencies were observed (105%) relative to the "B Level" performance goals established for 1979-1980 technology. The operating cell voltage was approximately 0.40 V at nominal pCO_2 levels of 400 Pa (3.0 mm Hg). This testing was performed at 6.9 kPa (1 psid) H_2 backpressure but later raised to 34.5 kPa (5 psid) for subsequent testing.

Design Verification Test. During design verification testing, cell UC-003 was characterized as a function of current density, H_2 backpressure, inlet RH and outlet RH over a total of 574 hours of operation. The baseline operating conditions, which were maintained during tests unless indicated otherwise, are provided in Table 10.

Very high CO_2 removal efficiency was observed for this single cell. This improved performance can be related to the more uniform support supplied to the electrochemical cell in the unitized core construction and to the uniform operating temperature of a liquid cooled EDC.

The unitized core was initially tested at 6.9 kPa (1 psi) H_2 backpressure to provide a baseline reference to previous cell performance. The backpressure was then increased to 34.5 kPa (5.0 psid). The decrease in CO_2 removal efficiency and cell voltage with increasing H_2 backpressure, as shown in Figure 26, is related to the location and the amount of electrolyte in the electrode/matrix/electrode sandwich. The electrolyte shifts from the anode toward the cathode with increasing H_2 backpressure.

The effects of variable current density on cell performance are shown in Figure 27 for operation both at 6.9 kPa (1.0 psid) and 34.5 kPa (5.0 psid) H_2 backpressures. The CO_2 removal performance surpassed the "B Level" goals of 1979-1980.

The cell was characterized as a function of inlet RH while the outlet RH was controlled to 55 ±3% RH as shown in Figure 28. The single cell demonstrated an excellent inlet RH tolerance range, with only minor variations in CO_2 removal efficiency between 37.5% and 82% RH, well above the "B Level" goals.

The range of outlet RH's produced by the liquid-cooled cells was narrower than the corresponding RH range of the inlet air. The major portion of the surface area of such EDC cells operates at or very near the outlet RH. Accordingly, the outlet RH range (over which CO_2 removal efficiency varied minimally) was correspondingly smaller than the inlet RH range, as shown in Figure 29. The absolute efficiency of cell UC-003 of course decreased at current densities above the baseline value of 21.5 mA/cm^2 (20.0 ASF) (see Figure 27).

Full Scale Module Evaluation - Test Stand Development

Following successful evaluation of the full-scale unitized core single cell, a complete module incorporating six cells like UC-003 was fabricated, assembled

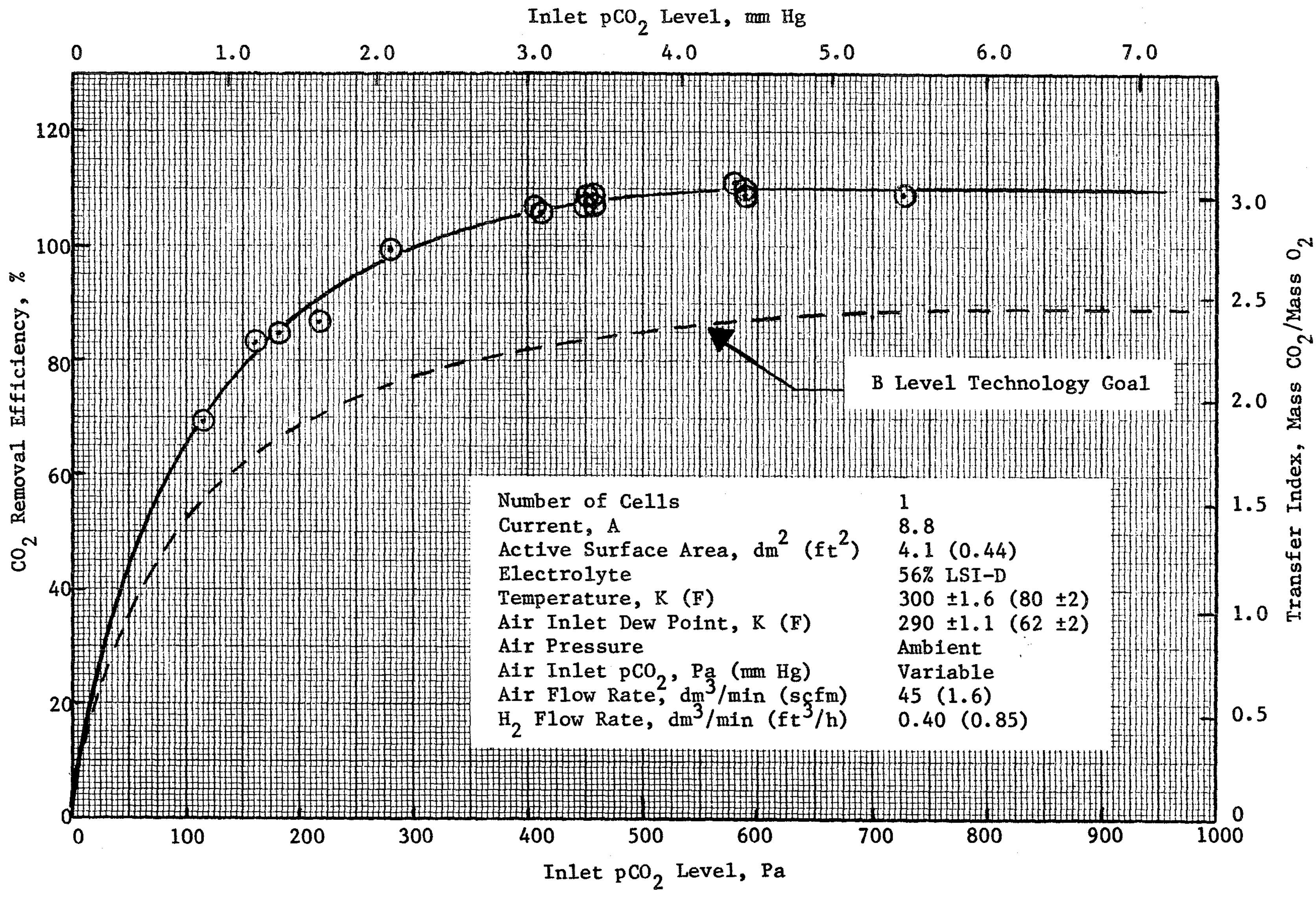


FIGURE 25 PERFORMANCE OF UNITIZED CORE CELL (UC-003) AS FUNCTION OF INLET pCO_2 LEVEL

TABLE 10 BASELINE OPERATING CONDITIONS FOR SINGLE CELL UNITIZED CORE (UC-003) TESTING

pCO_2, Pa (mm Hg)	400 (3.0)
Current Density, mA/cm^2 (ASF)	21.5 (20)
Air Flow/Cell,[a] dm^3/min (scfm)	4.5 (1.6)
Inlet Process Air Temperature, K (F)	296 ±3 (73 ±5)
Inlet RH, %	60 ±4
Outlet RH, %	55 ±5
H_2 + CO_2 Backpressure, kPa (psid)	34.5 (5.0)

(a) For a 4.1 dm^2 (0.44 ft^2 active cell area)

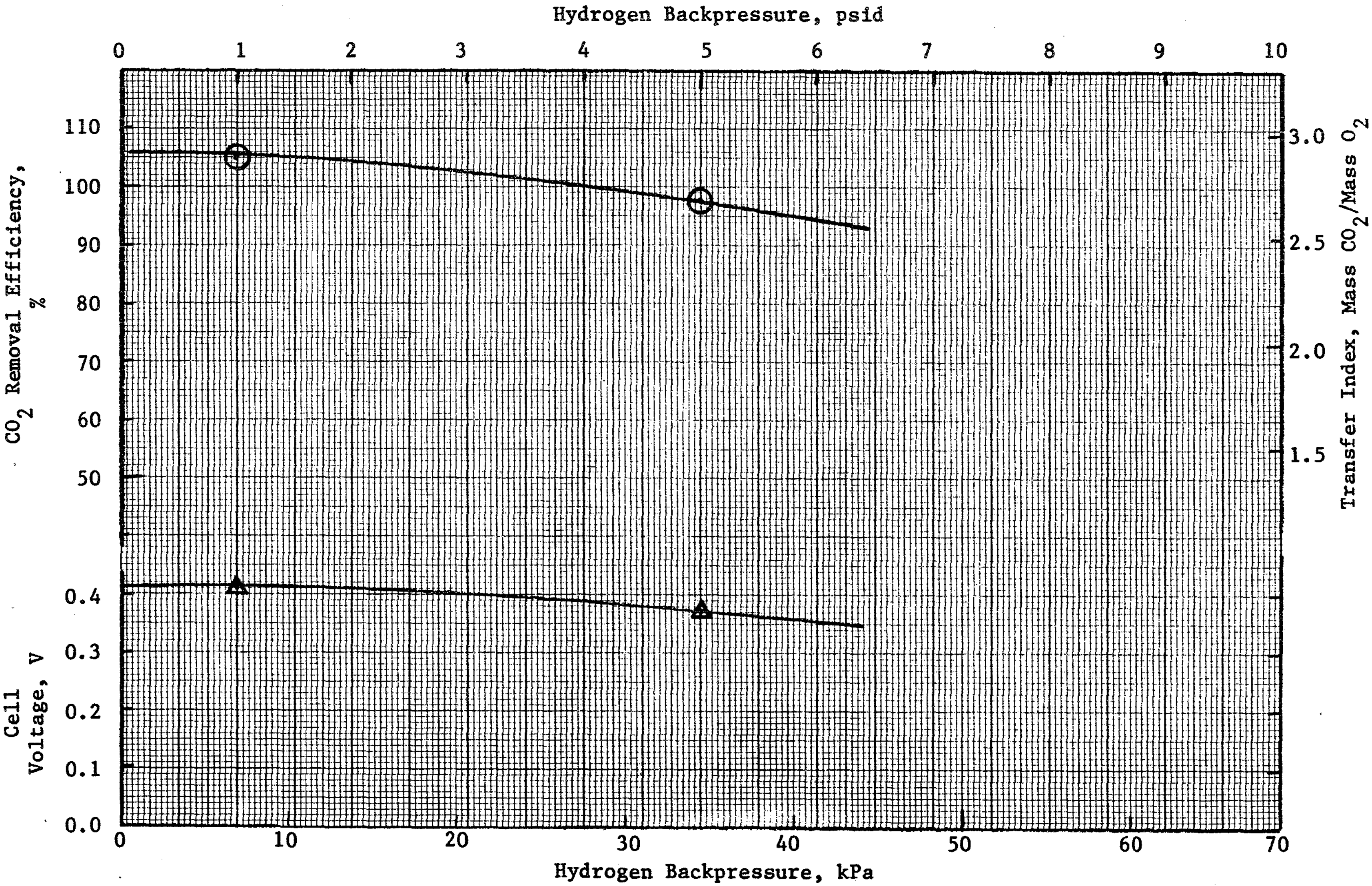


FIGURE 26 UNITIZED CORE (UC-003) SINGLE CELL PERFORMANCE AS FUNCTIONAL HYDROGEN BACKPRESSURE

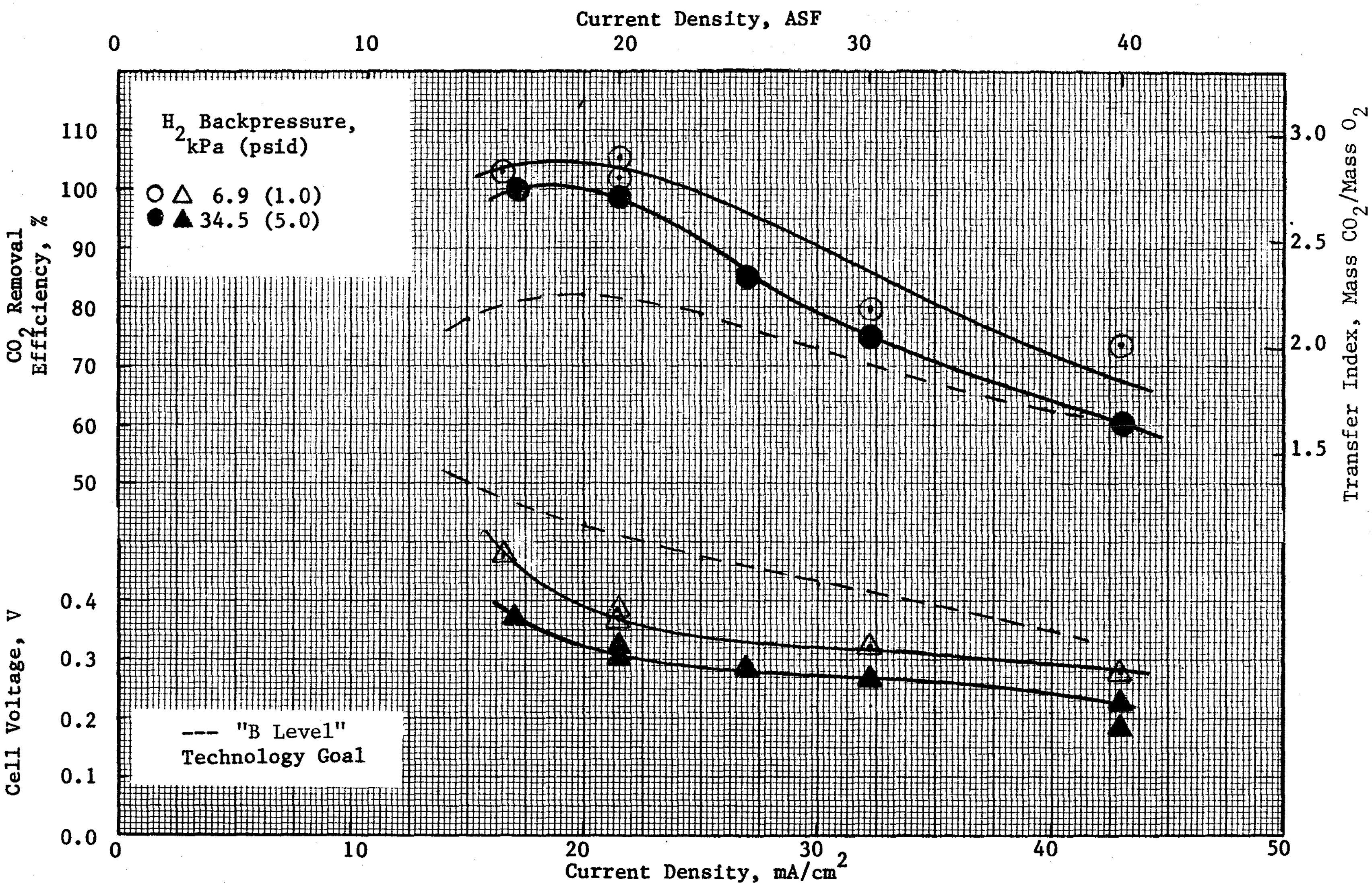


FIGURE 27 UNITIZED CORE (UC-003) SINGLE CELL PERFORMANCE AS A FUNCTION OF CURRENT DENSITY

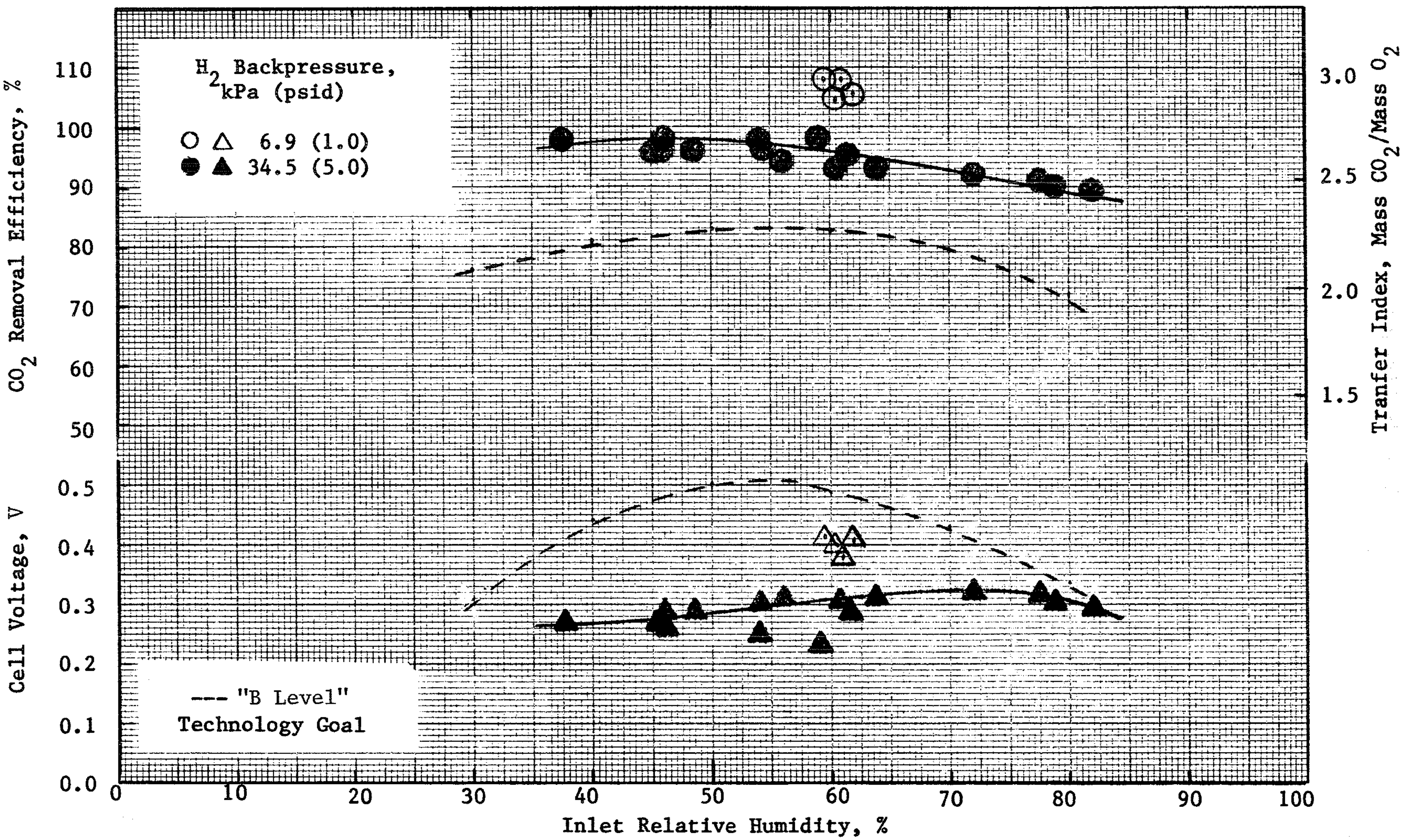


FIGURE 28 UNITIZED CORE (UC-003) SINGLE PERFORMANCE AS FUNCTION OF INLET RELATIVE HUMIDITY

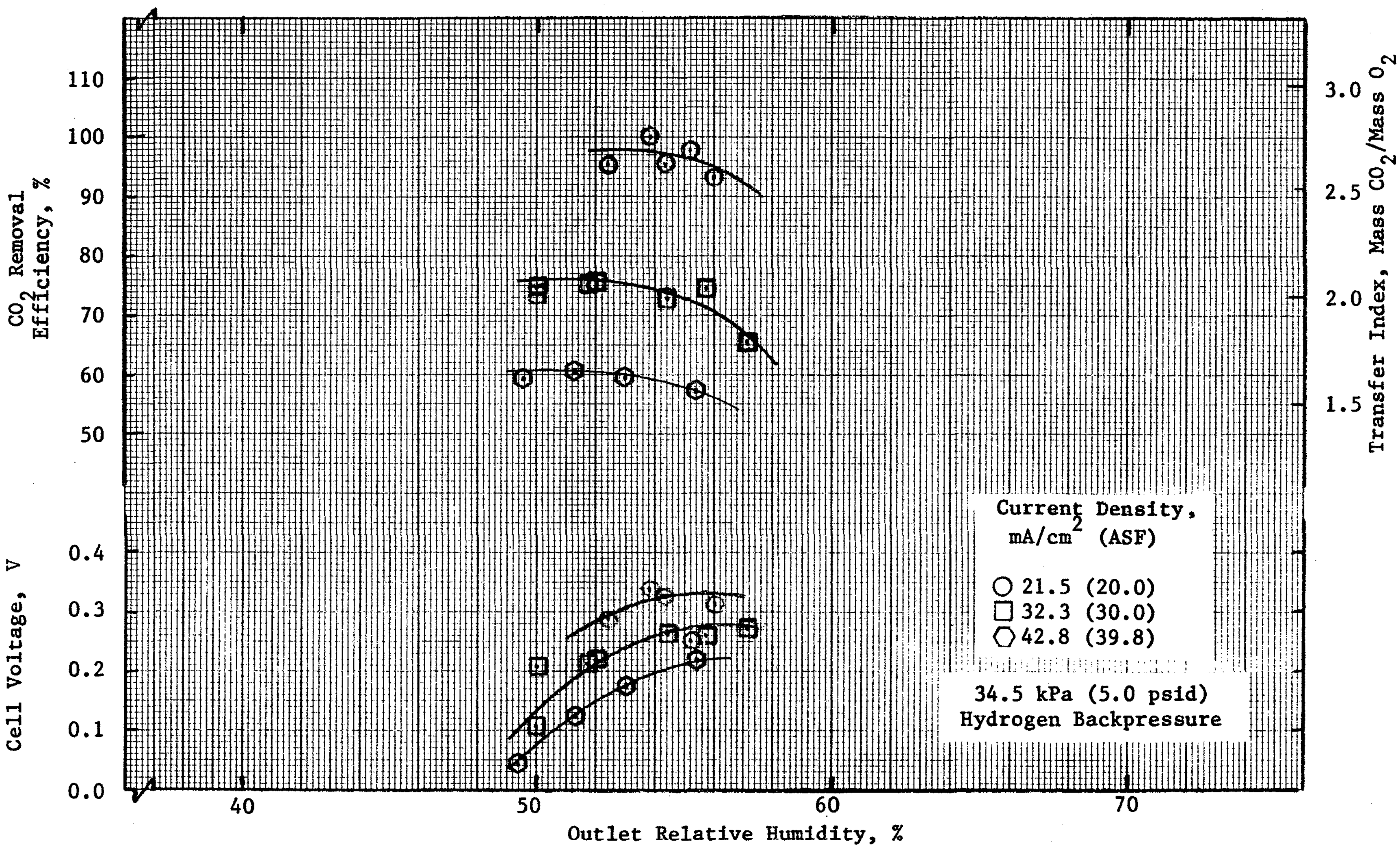


FIGURE 29 UNITIZED CORE (UC-003) SINGLE CELL PERFORMANCE AS FUNCTION OF OUTLET RELATIVE HUMIDITY

and tested. The six-cell tests required development of a special, high capacity test stand to simulate module application conditions and reliably control and monitor operation. This is discussed in detail below. The module evaluation is discussed subsequently.

General Description

The mechanical test stand hardware is described pictorially in Figure 30 and schematically in Figure 31. Laboratory air is humidified with make-up water, temperature regulated and blown into the EDCM via the gas humidifier. The EDCM inlet and outlet dew points and temperatures are monitored with D1, D2, T1 and T2, respectively. Heat exchanger HX2, is effectually a part of the EDCM and preadjusts the simulated cabin air temperature to the module temperature (HX2 performs the same function as the heat exchanger that will be located in the air inlet duct of the advanced module). The CO_2 content of the air simulant is regulated at F2 and periodically sampled for analysis through MV5, both for the EDCM inlet and outlet.

The H_2 supply to the module is regulated through F1. Both the H_2 supply and N_2 purge gas are humidified in GH2 prior to entering the module. Trap TR1 ensures that no liquid water will inadvertantly be swept into the module. Hydrogen backpressure is regulated at PR1 and monitored at P1 and P2.

The CCA regulates the module temperature. It does this by regulating the flow of heat exchanger fluid through and/or around HX1 and circulating it through the module and HX2 via a diverter valve and pump, the latter two components being part of the CCA.

This test stand was designed to provide for unattended EDCM operation for long periods while minimizing testing labor hours/cost. This was effectively accomplished by incorporating electronic packages that automatically control and monitor the CO_2 removal process and other packages to automatically protect against failure situations. Instrumentation for monitoring operating temperatures, pressures, RH's, cell current and cell voltages is also provided. Operating/protection modes are described below.

Operating Modes

The test stand was designed with four modes - three operating and one non-operating - and nine mode transitions.

Normal Mode. In the normal mode, the EDCM is concentrating CO_2 from the process air to the H_2 outlet stream. The normal mode is called for by:

a. Manual actuation

Shutdown Mode. In the shutdown mode, the EDCM is not removing CO_2. Module current is zero and all actuators are deenergized. The test stand is powered and all sensors are working. The shutdown mode is called for by:

a. Manual actuation

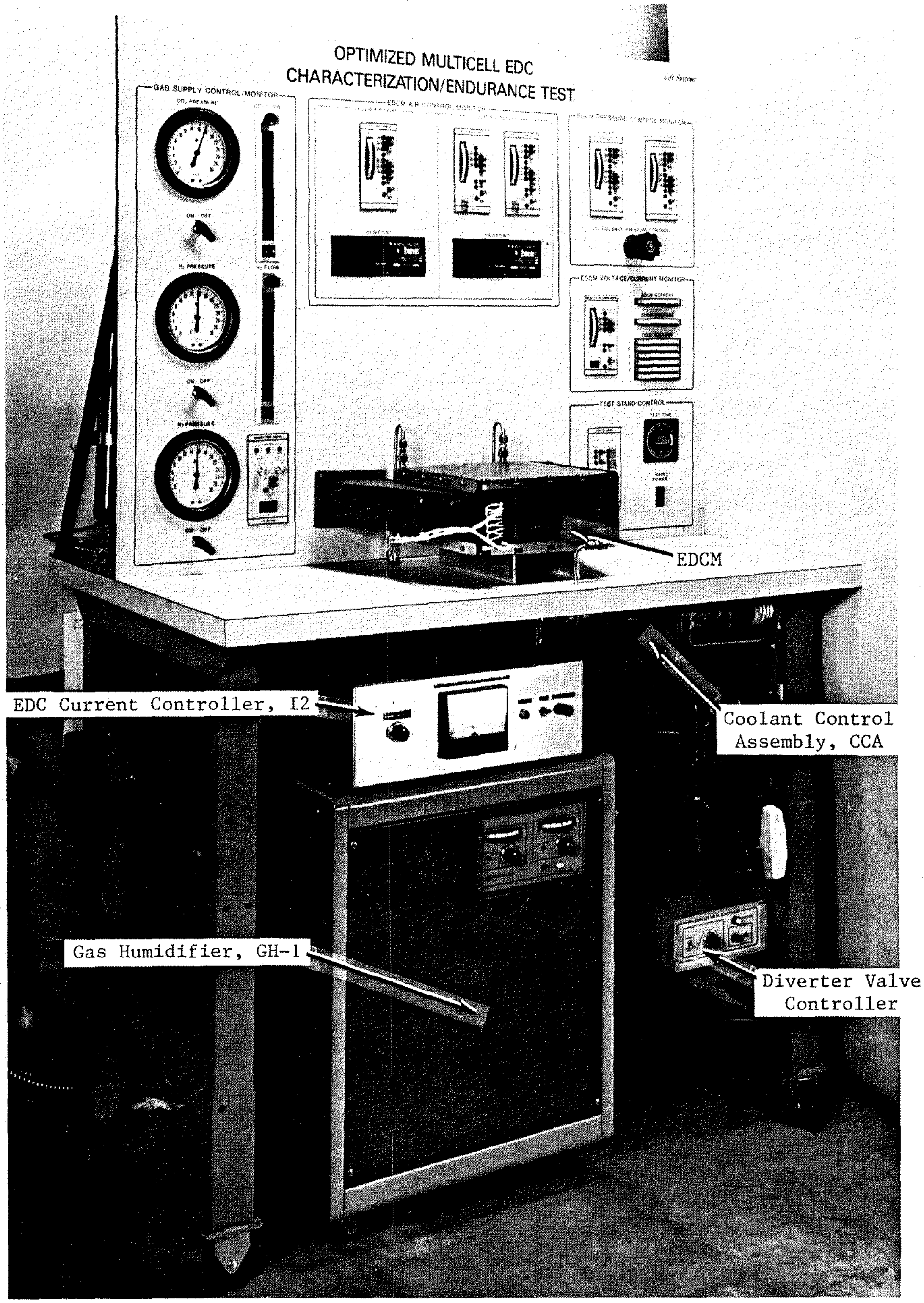


FIGURE 30 MULTICELL EDC TEST STAND

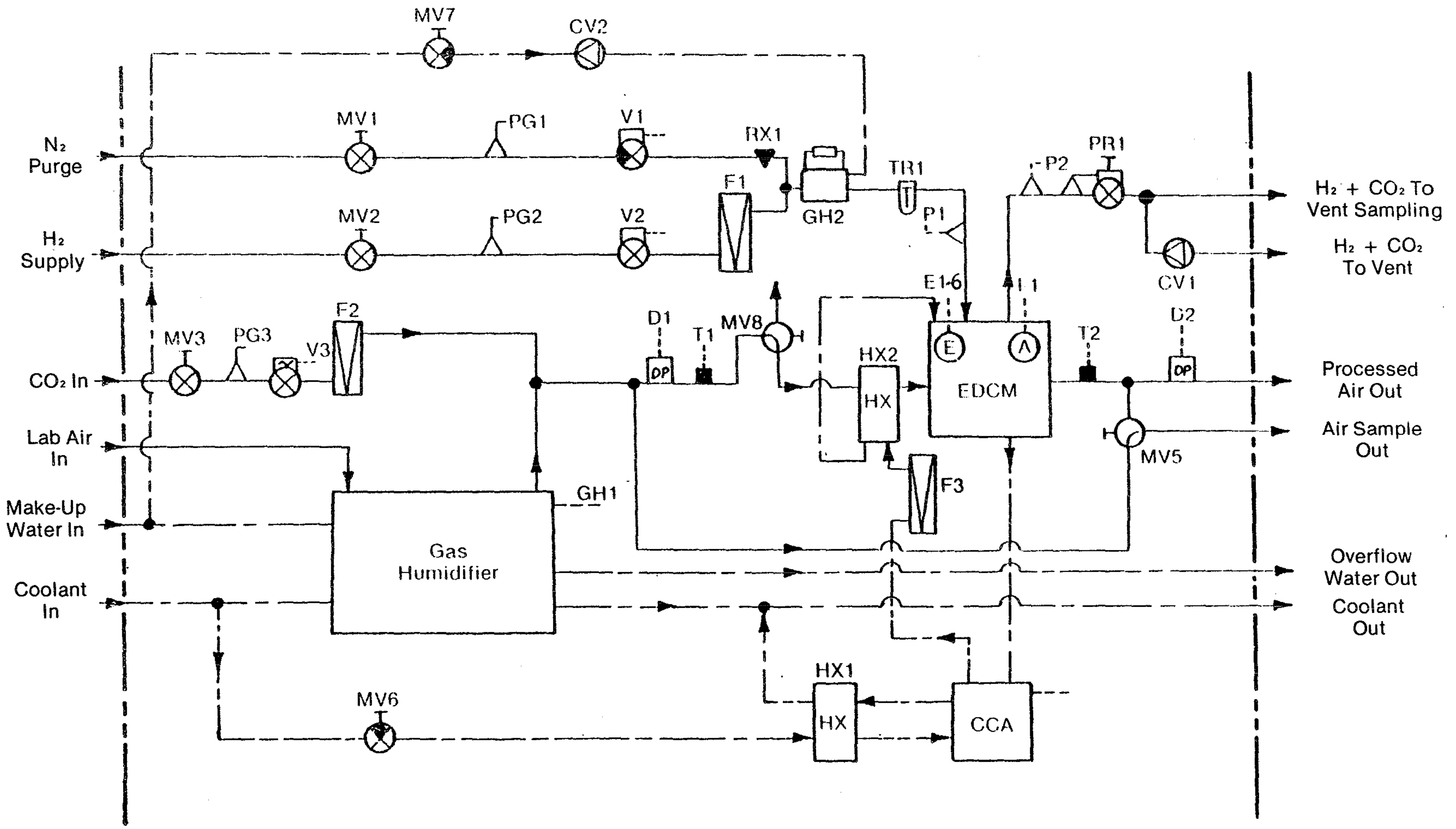


FIGURE 31 MULTICELL EDC TEST STAND MECHANICAL SCHEMATIC

b. Low cell voltage (E1-E6)[a]
c. High inlet process air RH (D1, T1)
d. Low inlet process air RH (D1, T1)
e. High outlet process air RH (D2, T2)
f. Low outlet process air RH (D2, T2)
g. High outlet process air temperature (T2)
h. High inlet H_2 pressure (P1)
i. Low outlet H_2/CO_2 backpressure (P2)

Standby Mode. In the standby mode, the EDCM is ready to perform its function. The system is powered and all system operating parameters are within acceptable limits. The inlet process air is diverted from the EDCM to ambient by a manual valve in the process air stream (MV8). The standby mode is called for by:

a. Manual actuation

Unpowered Mode. The unpowered mode is a non-operating mode. No electrical power is applied to the test stand. The unpowered mode is called for by:

a. Manual actuation
b. Electrical power failure

Electrical Controls

Figure 32 is an electrical functional block diagram of the multicell EDC test stand. It illustrates in a simplified yet comprehensive manner the integration of all test stand actuators and controls and EDCM electronics.

- The Operational Control (OpC) oversees overall test stand operation and the mode transitions described above.

- The EDCM current controller regulates the current passing through the EDCM, which is monitored with a current shunt and meter.

- The Temperature Controller and Monitor (TeCM) monitors the outlet process air temperature and regulates the temperature via the diverter valve and controller of the CCA.

- The Relative Humidity Monitor (RHM) monitors the process air inlet RH via the inlet air dew point and temperature.

- The Relative Humidity Controller and Monitor (RHCM) monitors the outlet process air temperature and dew point, calculates and displays RH and regulates RH by controlling module temperature via the diverter valve/controller of the CCA.

(a) These symbols designate sensors labeled in Figure 31.

- The diverter valve controller directs the diverter valve of the CCA to appropriately regulate the flow through and/or around HX1, either in response to the RHCM (terminal B in Figure 32) or to the temperature controller and monitor (terminal A).

- Pressure and multiple cell voltage monitors (PM1, PM2, MCVM) and controllers for the nitrogen purge function (NPC) are also provided. The pressure and voltage monitors initiate shutdown signals if safe operating limits are exceeded.

Key Mechanical Components

Gas Humidifier. The gas humidifier supplies air at specified RH and dew point conditions. This unit is shown integrated with the test stand in Figure 30 and with the enclosure panel removed in Figure 33. The mechanical schematic is shown in Figure 34. The gas humidifier performs the following functions:

- A saturator tank assembly conditions lab air to the desired dew point level.

- A process air blower moves air through the humidifier and the EDCM.

- An air heater controls the process air RH by setting the dry bulb temperature at a specified differential above the dew point temperature.

- A controller performs the dew point, differential temperature and shutdown logic control. The gas humidifier operates as an independent process and can be shut down by an external signal. If shut down, the gas humidifier will also send a shutdown signal for external use.

- An enclosure houses the gas humidifier and provides the interfaces with facility resources and the item receiving the humidified air.

Coolant Control Assembly. The CCA is a breadboard of the prototype version developed and evaluated during this contractual effort. It consists of a circulating pump, an LSI diverter valve and controller unit and an accumulator to allow for coolant expansion and contraction. The function and operation is similar to that of the integrated prototype CCA, discussed in a separate chapter of this report.

Full Scale Module Evaluation - Test Program

Testing of the six-cell EDCM followed fabrication of the module and test stand. These tests are described below.

Checkout Testing

During checkout all test stand control circuits, shutdown points and sensor calibrations were verified.

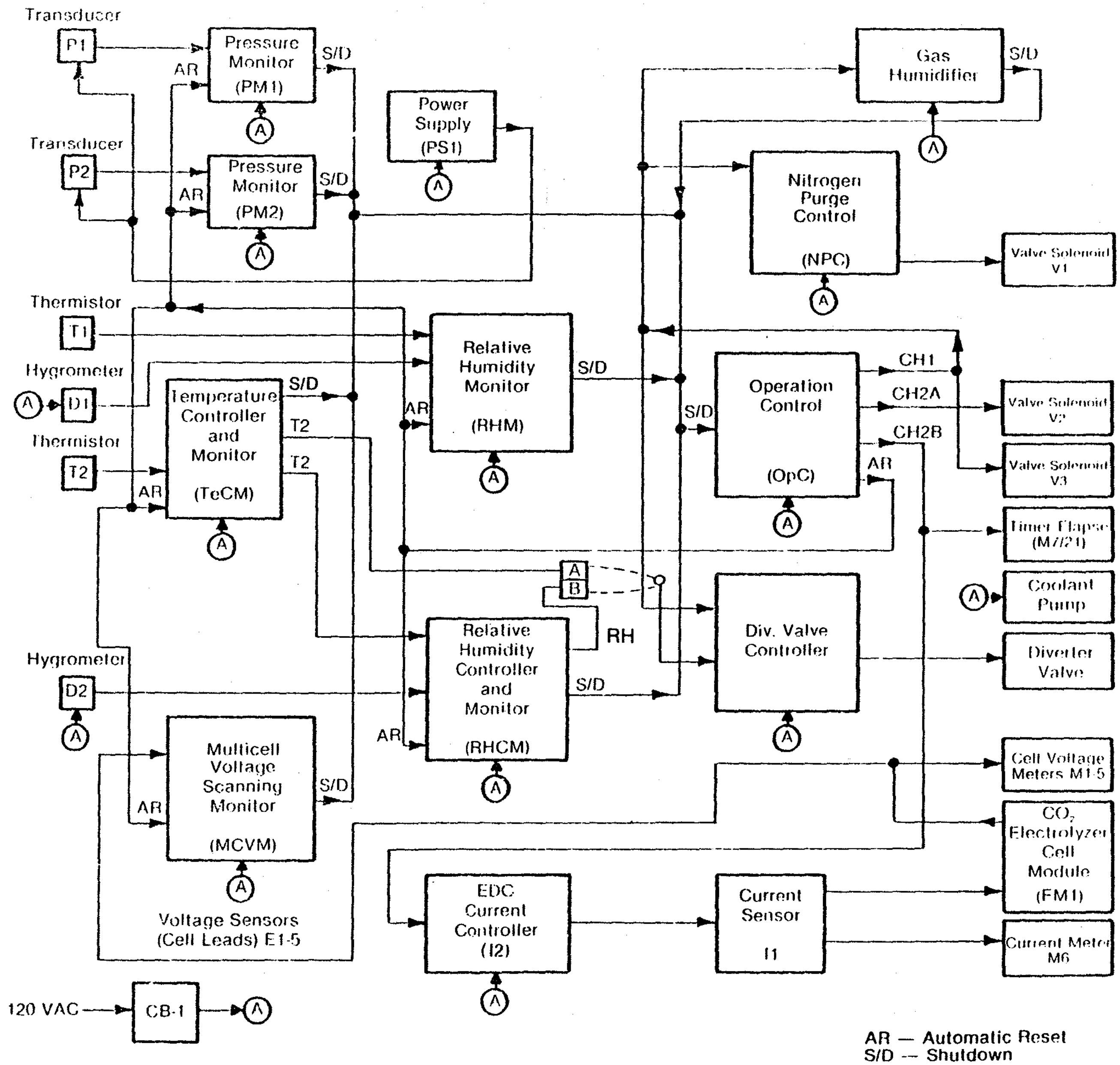


FIGURE 32 MULTICELL EDC TEST STAND ELECTRICAL FUNCTIONAL BLOCK DIAGRAM

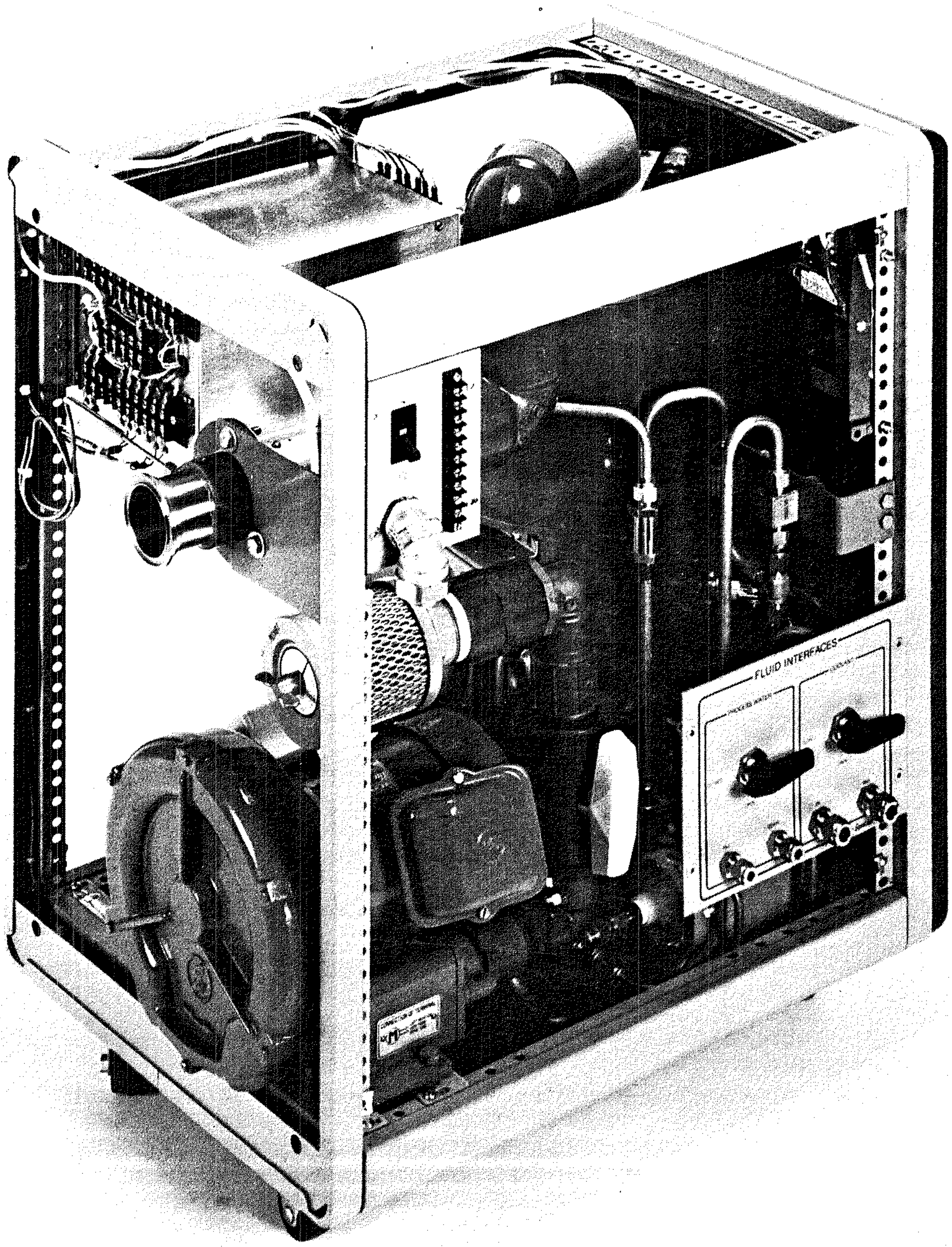


FIGURE 33 GAS HUMIDIFIER (WITHOUT ENCLOSURE)

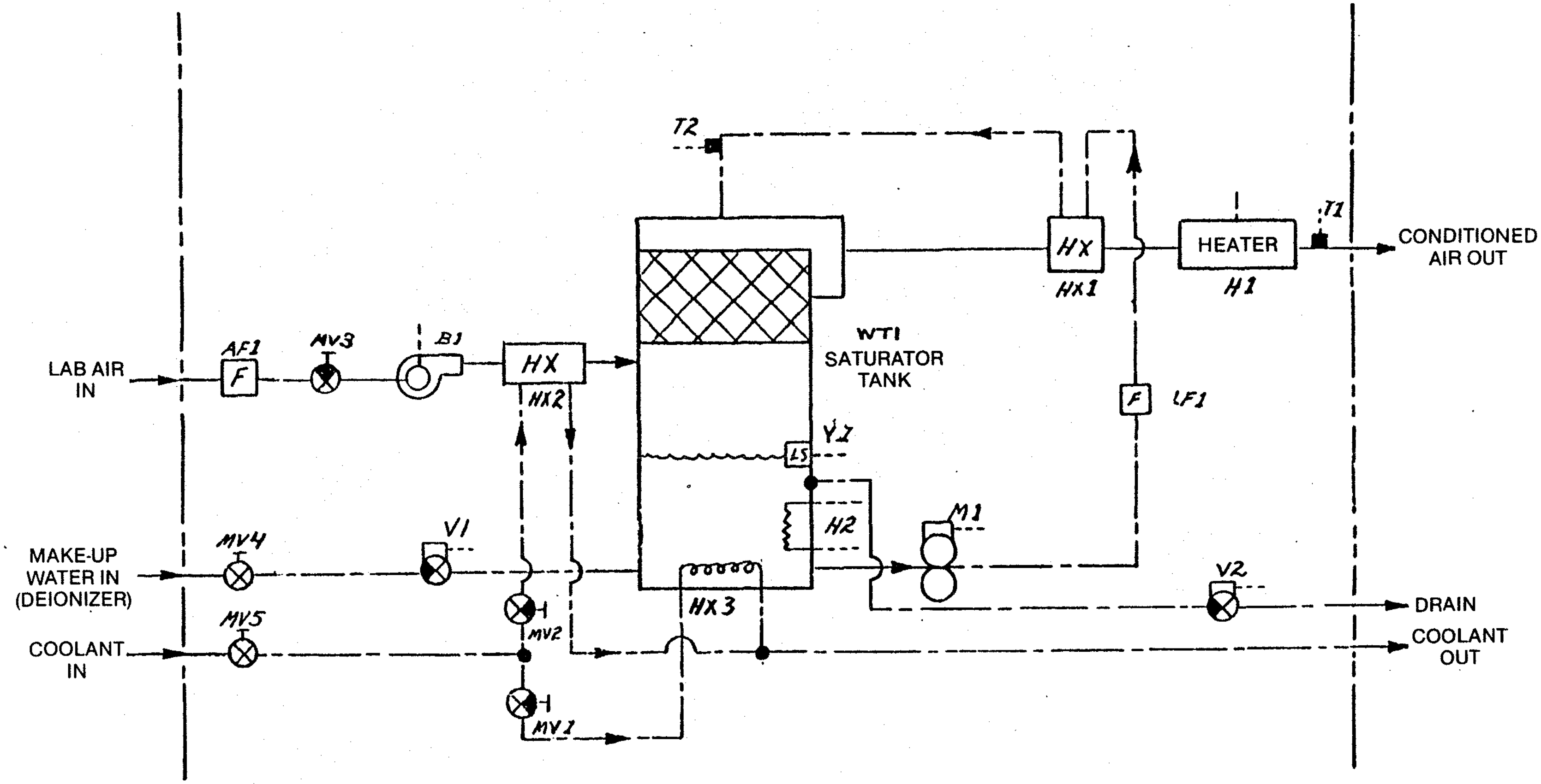


FIGURE 34 GAS HUMIDIFIER MECHANICAL SCHEMATIC

Shakedown Testing

Shakedown test included a continuous operation over 24 hours under nominal baseline conditions. Subsequently, the shutdown and restart capabilities of the integrated module and the test stand operational limits were verified.

Design Verification Test

The Design Verification Test (DVT) provided data over the design range of operating conditions to define nominal operating characteristics of the module and establish best operating conditions. These are listed in Tables 11 and 12, respectively. The established conditions were maintained during the test program unless varied parametrically or otherwise specified.

Parametric Tests

The parametric tests established the effects of CO_2 partial pressure (pCO_2), inlet RH and current density on module performance. These tests were performed both after the endurance test, as well as before, to investigate the effects of long term operation, totalling 3,000 hr.

Effect of Variable CO_2 Partial Pressure. EDCM performance at various pCO_2 levels is shown in Figure 35. The CO_2 efficiency averaged 90% (well above the 80% design point) at a nominal pCO_2 level of 400 Pa (3.0 mm Hg) and an anode exhaust (H_2) backpressure of 34.5 kPa (5.0 psig).

Current Density Effects. A comparison of the EDCM performance of pre- and post-endurance current density spans is shown in Figure 36. This shows that excellent CO_2 removal performance was maintained during long term operation (including an extended low RH interval). There was actually an increase in the CO_2 removal efficiency at the baseline current density, 21.5 mA/cm^2 (20 ASF), after the endurance test.

RH Effects. The effect of variable humidity on EDCM performance was investigated over the range 30 to 72% RH during the parametric tests. Additionally, low RH tolerance was explored during the endurance test (see below).

Data from both tests are plotted in Figure 37. Carbon dioxide removal efficiency, averaging over 90%, was almost unaffected by variable RH's. The average performance even improved following the endurance test. These accomplishments are attributed to the unitized core construction and to use of a process air heat exchanger upstream of the module. The heat exchanger preconditions the air to module temperature, thereby minimizing temperature and RH gradients in the cells and permitting larger inlet RH variations.

Endurance Test

The endurance test established the ability of the module to maintain acceptable performance while running continuously for 90 days (2,160 h). Conditions were typically maintained within the ranges listed in Table 12 during the majority of the test. However, the module was also operated over 700 h at 16 to 24% RH to demonstrate its ability to maintain acceptable performance at continuously very low RH's.

TABLE 11 MODULE OPERATING CHARACTERISTICS

Number of Cells	6
Active Area per Cell, cm^2 (ft^2)	409 (0.44)
Current Density (Nominal), mA/cm^2 (ASF)	21.5 (20)
Cell Voltage (Nominal), V	0.40
Power Generated, W	24
Waste Heat Produced, W	50
CO_2 Removed, kg/d (lb/d)	0.83 (1.83)
O_2 Consumed, kg/d (lb/d)	0.38 (0.83)
H_2 Consumed, kg/d (lb/d)	0.05 (0.10)
Water Generated, kg/d (lb/d)	0.43 (0.94)
CO_2 Removal Efficiency, %	80

TABLE 12 NOMINAL TEST CONDITIONS

Current, A	8.8
Process Air	
pCO_2 level, Pa (mm Hg)	400 (3.0)
pO_2 level, kPa (psia)	22.1 (3.2)
Relative Humidity, %	54 - 62
Dry Bulb, K (F)	295±2 (72±4)
Hydrogen	
Flow Rate, kg/h (lb/h)	0.007 (0.013)
Relative Humidity, %	95
Module Backpressure, kPa (psid)	34.5 (5.0)
Purge Gas	
Type	Nitrogen
Supply Pressure, kPa (psia)	207 (30)
Coolant (Water) Temperature, K (F)	Variable

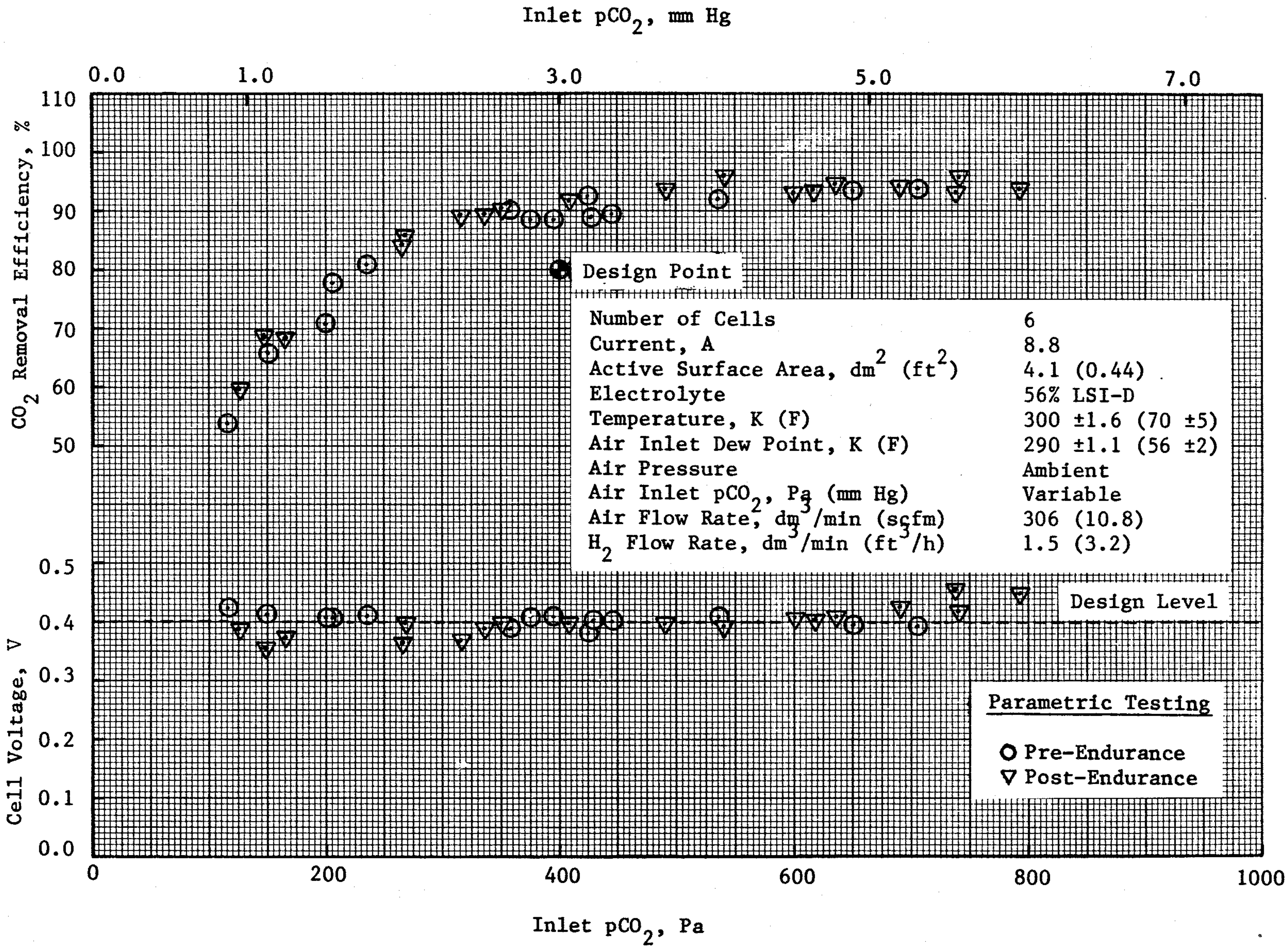


FIGURE 35 EFFECT OF CO_2 PARTIAL PRESSURE ON MODULE PERFORMANCE

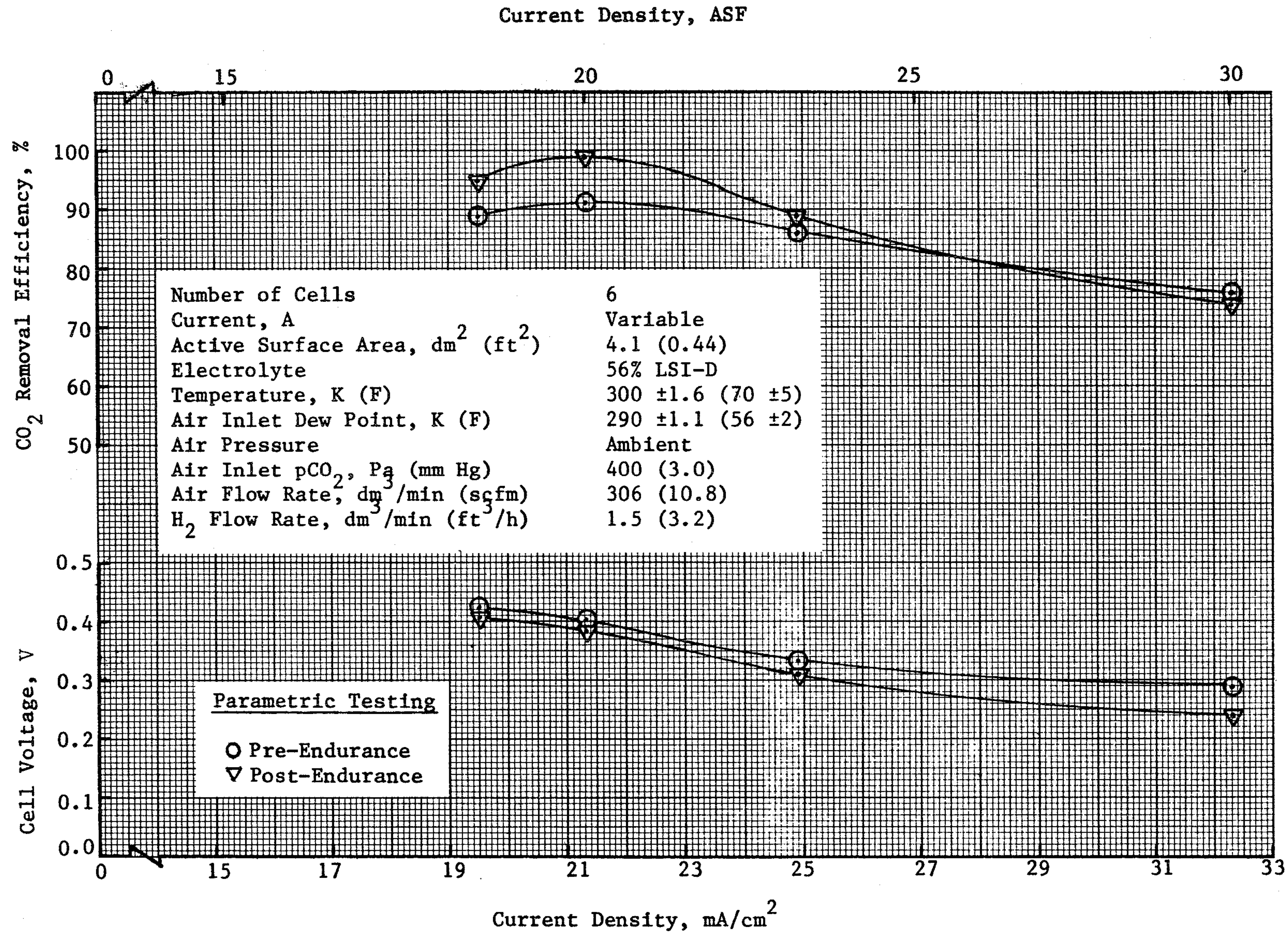


FIGURE 36 EFFECT OF OPERATING CURRENT DENSITY ON MODULE PERFORMANCE

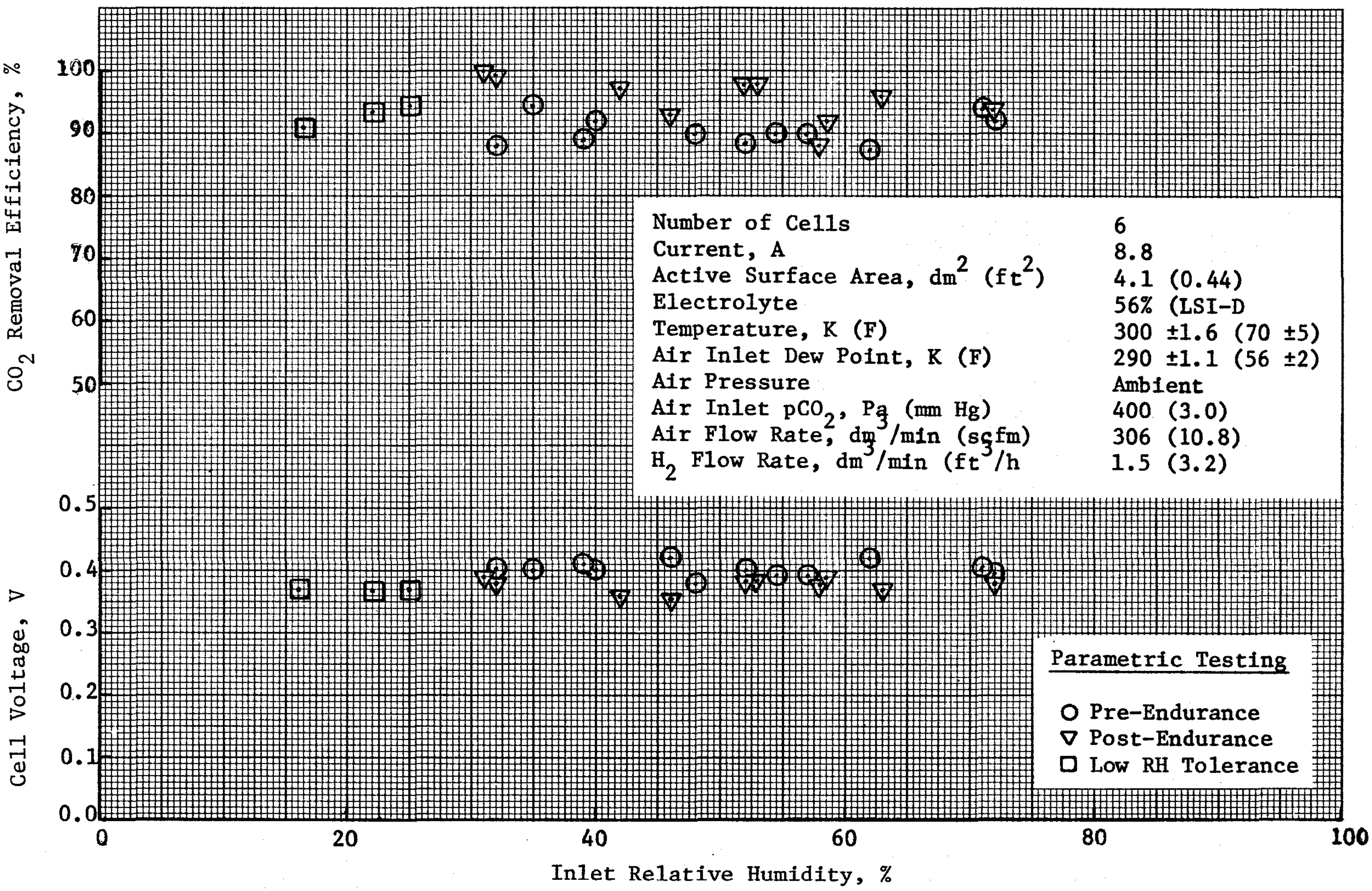


FIGURE 37 EFFECT OF RH ON MODULE PERFORMANCE

Performance during the entire 3,000 h of module operation, including the endurance test, is plotted in Figure 38 to maximize analysis of the data base. It is apparent that the CO_2 removal efficiency averaged greater than 90%, despite major perturbations in pCO_2 and extended operation between 16 and 24% RH. The stability of the electrochemical cells is also evidenced by the essentially constant 0.4 V cell voltage.

Conclusions

The results of these tests verify that the EDC development objectives have been met. Predictable, reproducible high level performance has been achieved over much wider ranges of RH and H_2 backpressure than heretofore achieved, both at the single cell and modular levels. This success is attributed to the development of unitized core, water cooled cells and, additionally, to ensuring that inlet air enters the EDCM preconditioned to module temperatures via a heat exchanger part of the subsystem. It is recommended that these innovations be incorporated into all future EDCM's. They should also be considered for adaptation in other spacecraft electrochemical modules (e.g., Water Vapor Electrolysis Modules (WVEM's)) to improve RH stability.

FLUIDS CONTROL ASSEMBLY DEVELOPMENT

Assembly Description

Control of H_2 flow, H_2 backpressure and N_2 flow to the EDCM, previously performed by eleven (11) discrete components, can now be accomplished by an integrated FCA weighing only 1.7 kg (3.8 lb) and occupying only 2,065 cm^3 (126 in^3). This device was shown schematically as part of Figure 8 and is depicted in Figure 39. It consists of a backpressure regulator mounted on a valve with a multiple function spool and a valve housing that has built-in orifices to limit H_2 and N_2 flow rates, sensors for monitoring upstream and downstream module pressures and sensors to monitor flow rates to and from the module. In addition the FCA has a manual override capability and a positive Valve Position Indicator (VPI) for use with the control electronics. Figure 40 shows the separated components. The number of fluid connections, total weight, total volume and total power required has been reduced, as well as the number of components. Also, the FCA provides for simple Line Replaceable Unit (LRU) in-flight maintenance. These uses and advantages were summarized in Table 5.

Table 13 contains the FCA Operating Characteristics and Conditions. Table 14 lists the sensors and actuators, as well as the valve positions that describe the multiple function valve spool.

Fluids Control Assembly Controller

General Description

The FCA Controller, shown in Figure 41 along with the mechanical assembly, contains all the circuits necessary to operate the LSI FCA. The controller orients the valve spool in any one of three operating positions. The mode selection can be made by a front panel control or by external digital signals through a back panel connector. A front panel indicator identifying the

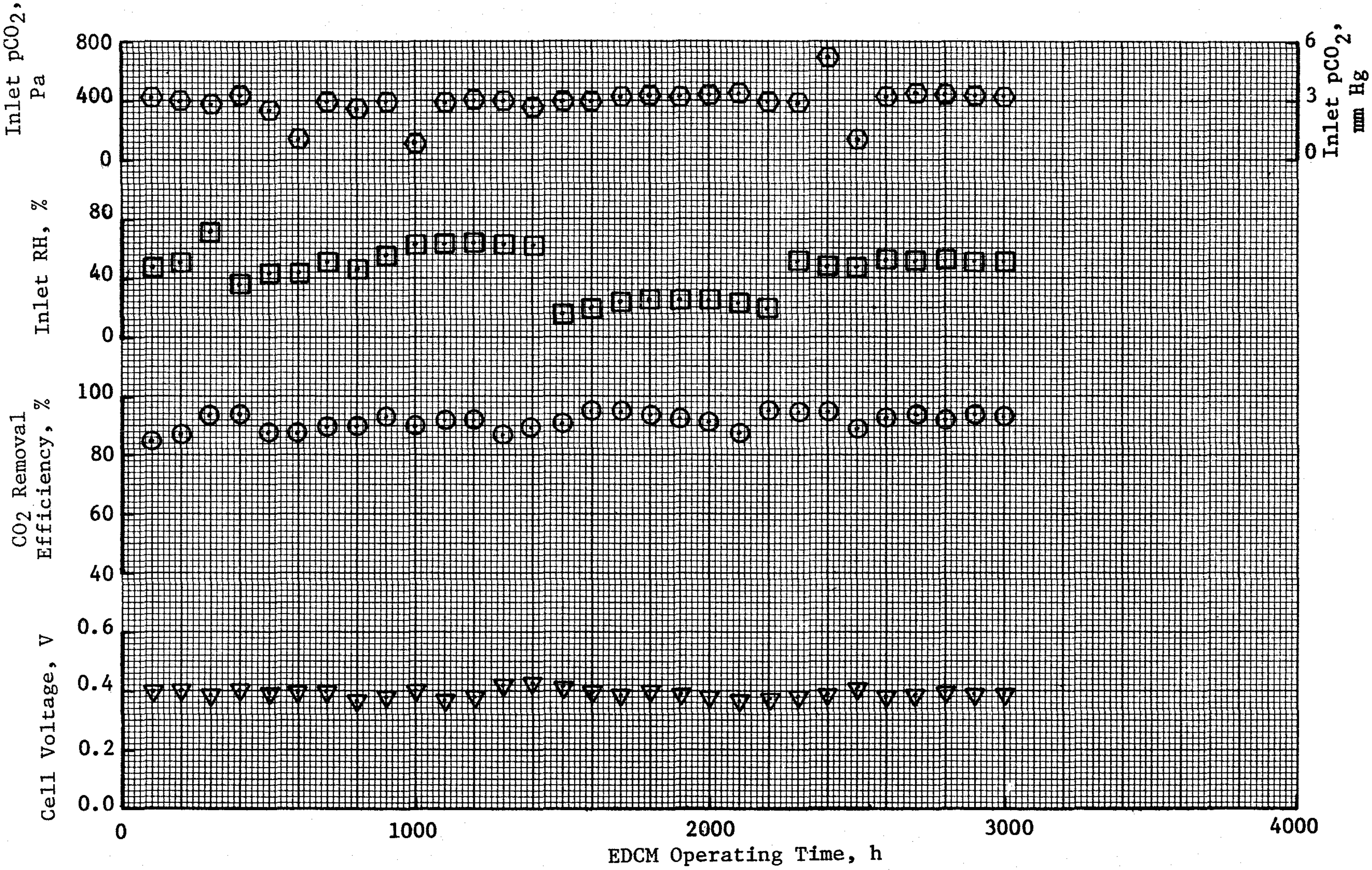


FIGURE 38 LONG TERM MODULE PERFORMANCE

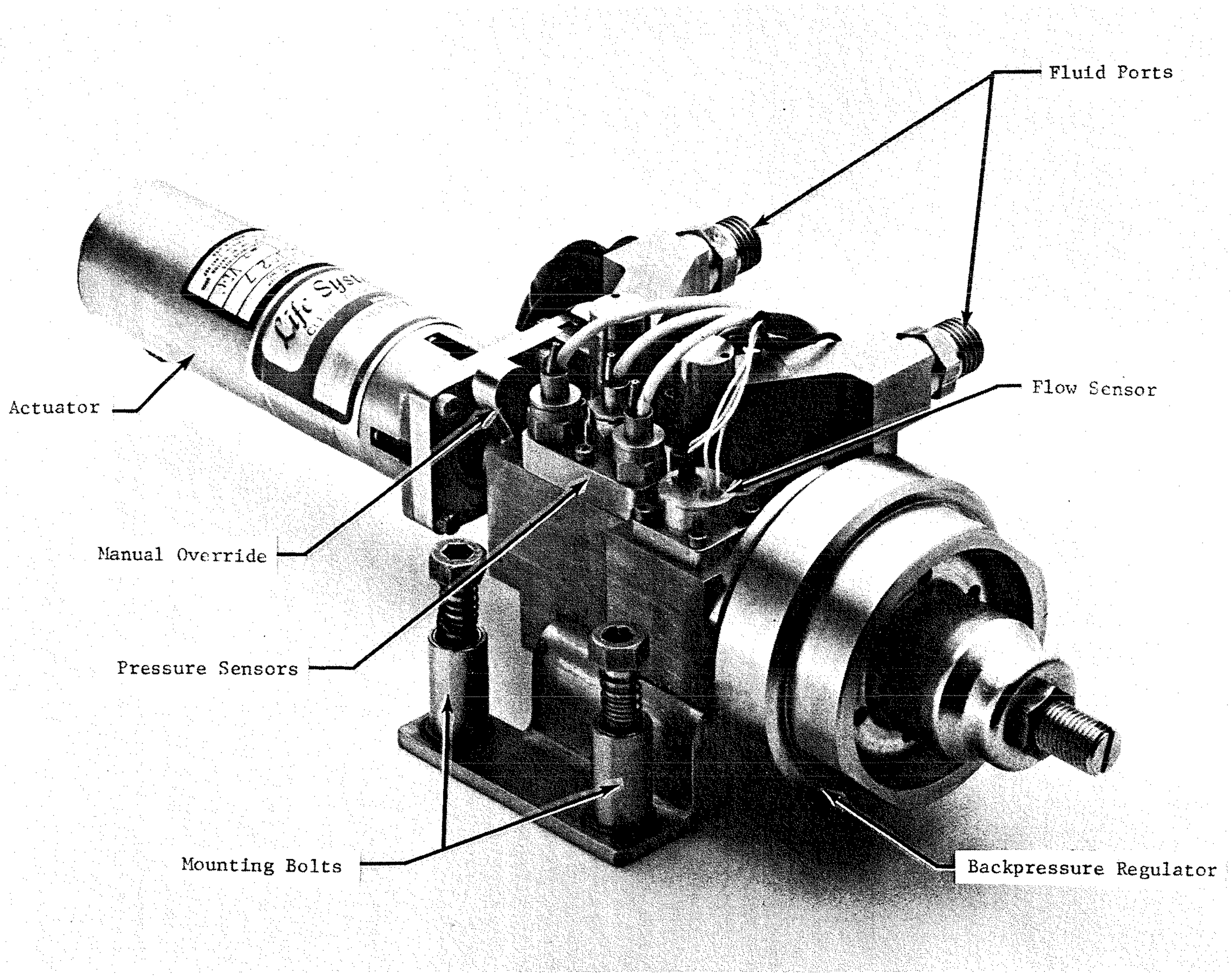


FIGURE 39 FLUIDS CONTROL ASSEMBLY PHOTOGRAPH

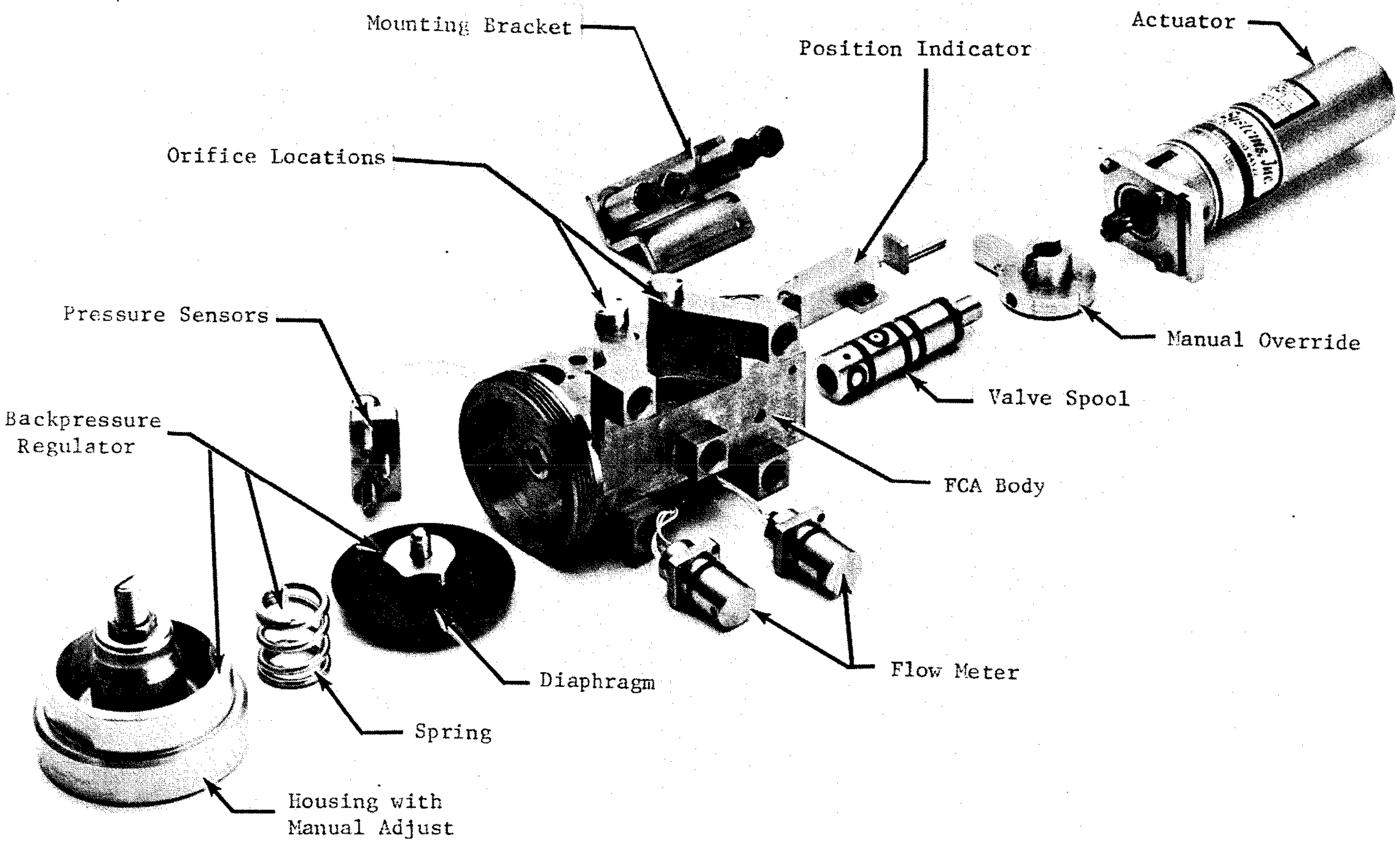


FIGURE 40 FLUIDS CONTROL ASSEMBLY EXPLODED VIEW

TABLE 13 FCA OPERATING CHARACTERISTICS AND CONDITIONS

Working Fluids	H_2, N_2, CO_2
Flow Rate, std. dm^3/min	
Nominal	3
Range	0 to 6
Regulated Pressure, kPa (psia)	
Range	974 to 103 (14 to 15)
N_2 Supply Pressure, kPa (psia)	
Nominal	827 (120)
Range	172 to 1482 (25 to 215)
H_2 Supply Pressure, kPa (psia)	
Nominal	172 (25)
Range	138 to 207 (20 to 30)
Temperature, K (F)	
Nominal	297 (75)
Range	289 to 305 (60 to 90)

TABLE 14 FCA SENSOR AND ACTUATOR LIST

Description	Quantity	Redundancy Level	Symbol
Sensor			
H_2 or N_2 Pressure	1	1	P1
Module Pressure	2	1	P2, P3
H_2 or N_2 Flow to Module	1	1	F1
Flow From Module	1	1	F2
Valve Position Indicator	1	1	W1
Total	6		
Actuator			
N_2, H_2, H_2/CO_2 Vent Control Valve (Four Position)[a]	1	1	V1

(a) V1 Operation Description

Position	N_2	H_2 Flow[b] Low	H_2 Flow[b] High	Vent[c]
1	O[d]	C	C	O
2	C	C	C	C
3	C	O	C	O
4	C	C	O	O

(b) Low H_2 flow position selected for Shuttle application and high H_2 flow selected for central CO_2 removal system application.
(c) The opening of the vent occurs 10 to 20 degrees prior to the opening of the N_2 or H_2 feed.
(d) O = Open; C = Closed

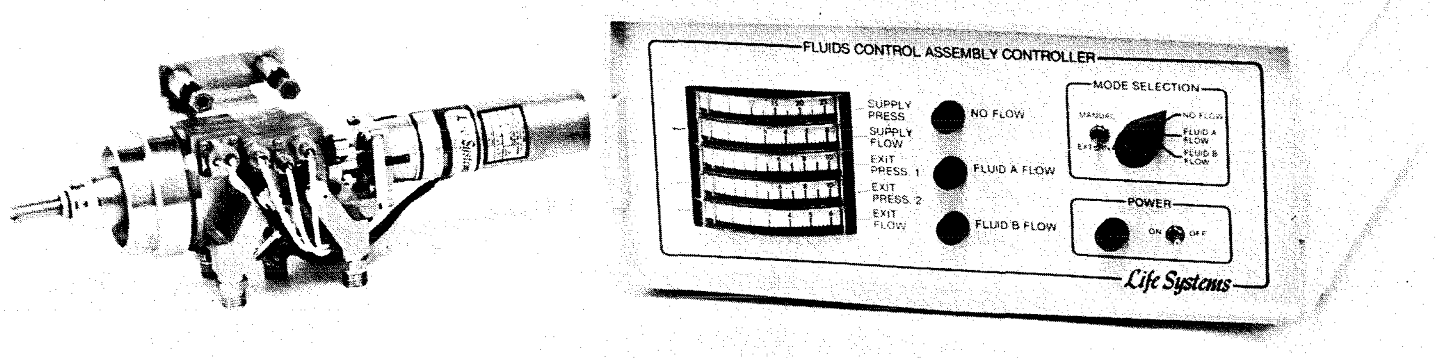


FIGURE 41 FLUIDS CONTROL ASSEMBLY AND CONTROLLER

selected valve position illuminates when the FCA reaches this position. Front panel meters display three pressures and two flows transmitted from the sensors of the FCA. The FCA controller operates on 115 V 60 Hz power and is contained in a 13.3 cm (5.3 in) high x 31.8 cm (12.5 in) wide x 29.5 cm (11.6 in) deep plastic enclosure.

Functional Description

The block diagram of Figure 42 shows the relationship between the various functional circuit elements inside the FCA controller. The FCA contains six sensors. Three of these sensors measure pressure, two measure flow, and one measures valve position. The signals from the pressure and flow sensors are conditioned and transmitted to front panel meters and back panel connectors. The signal from the valve position sensor, a linear variable differential transformer (LVDT), is conditioned and connected to a back panel connector and to the position controller logic.

The position controller logic compares the actual valve position signal from the LVDT with the selected valve position signal from a setpoint logic circuit and amplifies the difference. This difference, after power amplification, drives the FCA valve motor in the correct direction until the desired position is obtained (difference becomes zero).

The output from the setpoint selection logic is a 0 to 5 V DC signal, corresponding to a given valve position. Its magnitude depends on a digital signal from the override logic circuit. This signal is determined in turn, by either external mode selection signals or the Mode Selection switch position. This signal also governs which of the four Mode lamps should be lit. The selected lamp is lit when the position controller logic dictates to the error level detector that the FCA valve is in the proper position. The output of the error level detector also informs external circuits of this achievement.

Tests Support Accessory Development

Test Stand

A test stand was specifically fabricated for the FCA both to characterize its performance and demonstrate its endurance. This is shown in Figure 43, with the FCA mounted in place.

Figure 44 is the FCA test stand mechanical schematic. Hydrogen and N_2 are provided so that characterization testing may proceed under normal operating conditions. Compressed air is also provided so that the endurance testing may be conducted at lower cost.

Actuator Exerciser

The actuator exerciser, shown in Figure 45, is a digital device that provides a six line parallel digital output for programmed sequencing of controllers, such as the FCA, through four modes. The length of time in each mode can be varied between 7.5 to 60 minutes by the "Residence Time" control. The exerciser has two digital inputs: a "Reset" that puts the exerciser in state 1 and an "In Position" signal that activates the Residence Time timer.

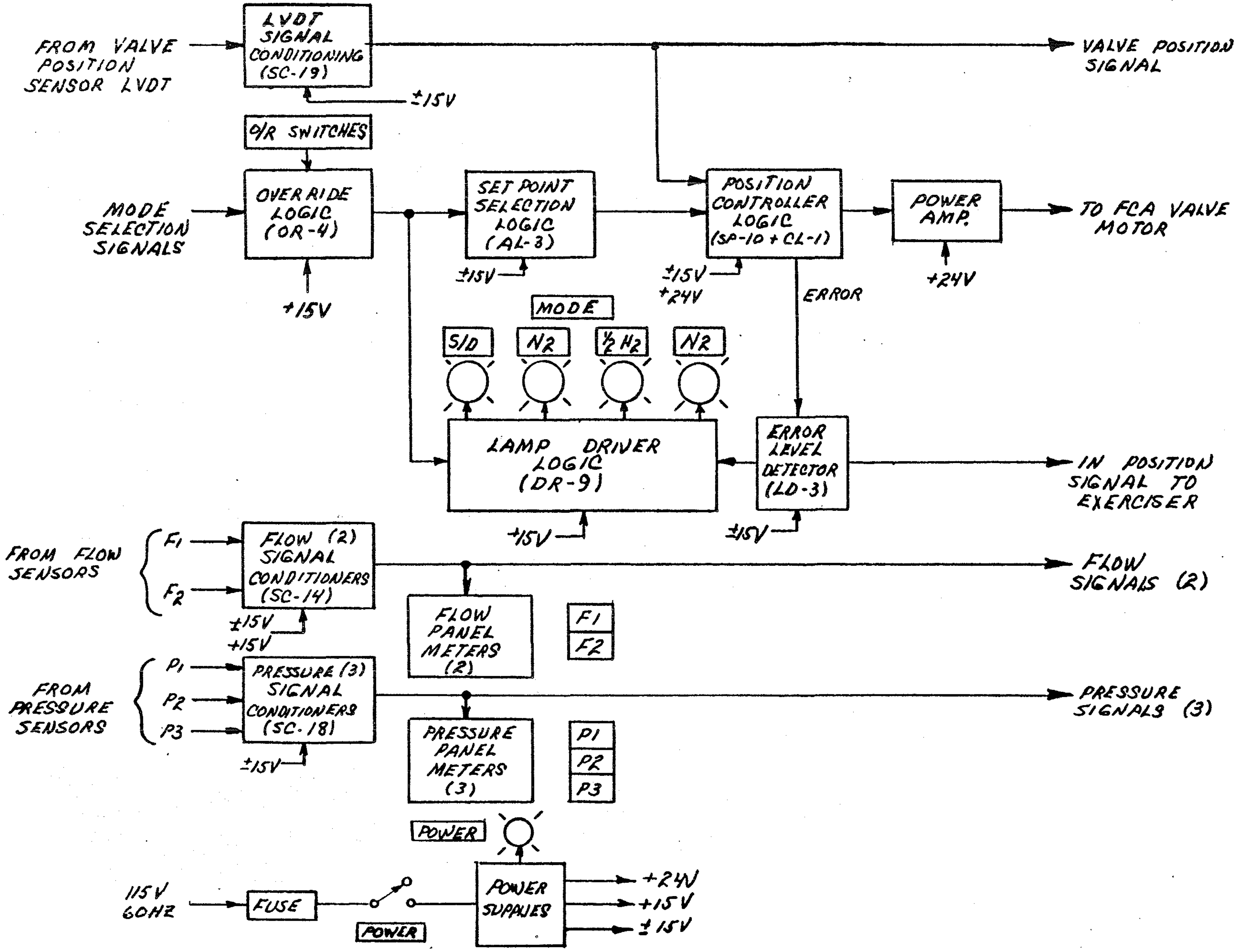


FIGURE 42 FCA CONTROLLER ELECTRICAL FUNCTIONAL BLOCK DIAGRAM

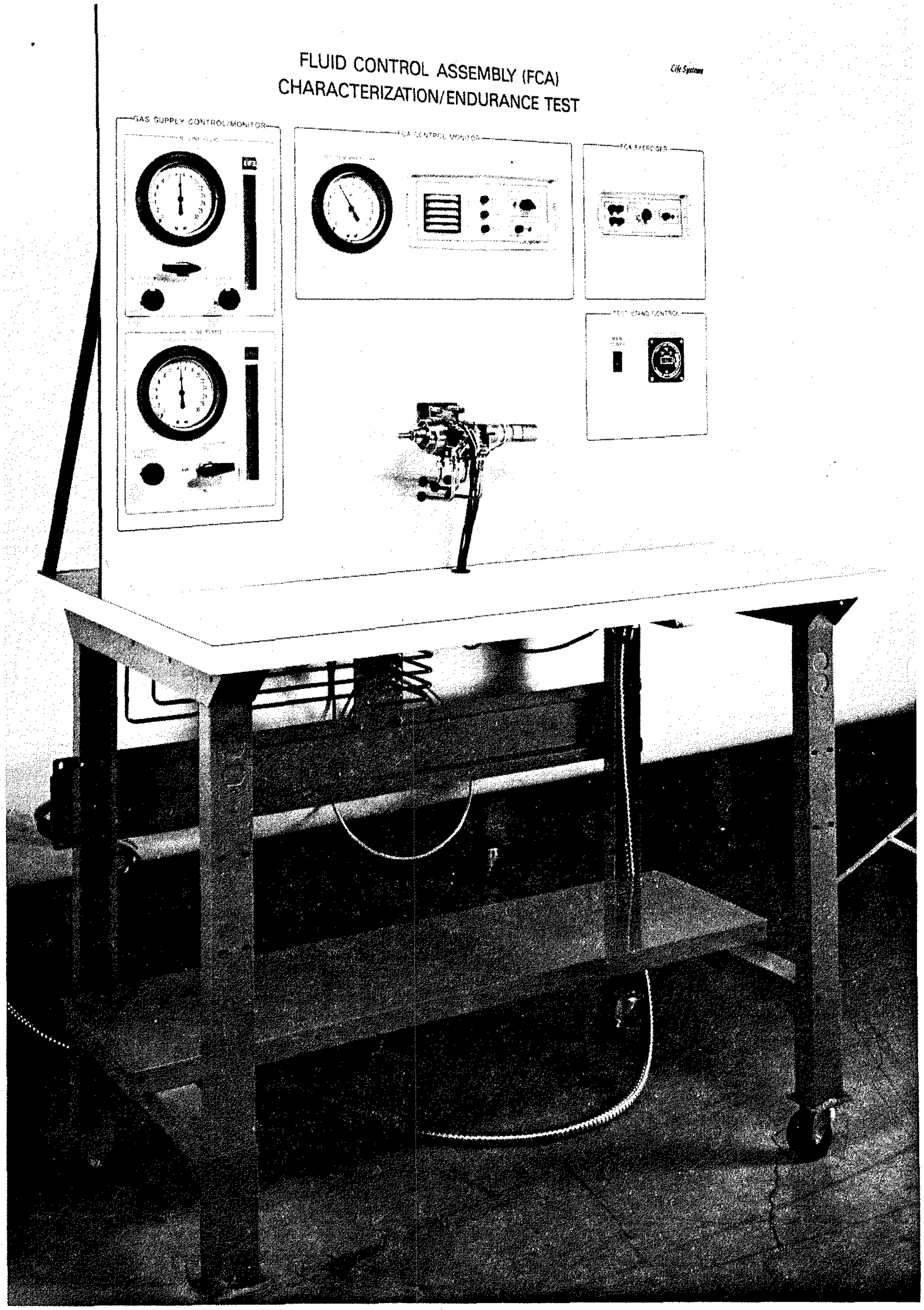
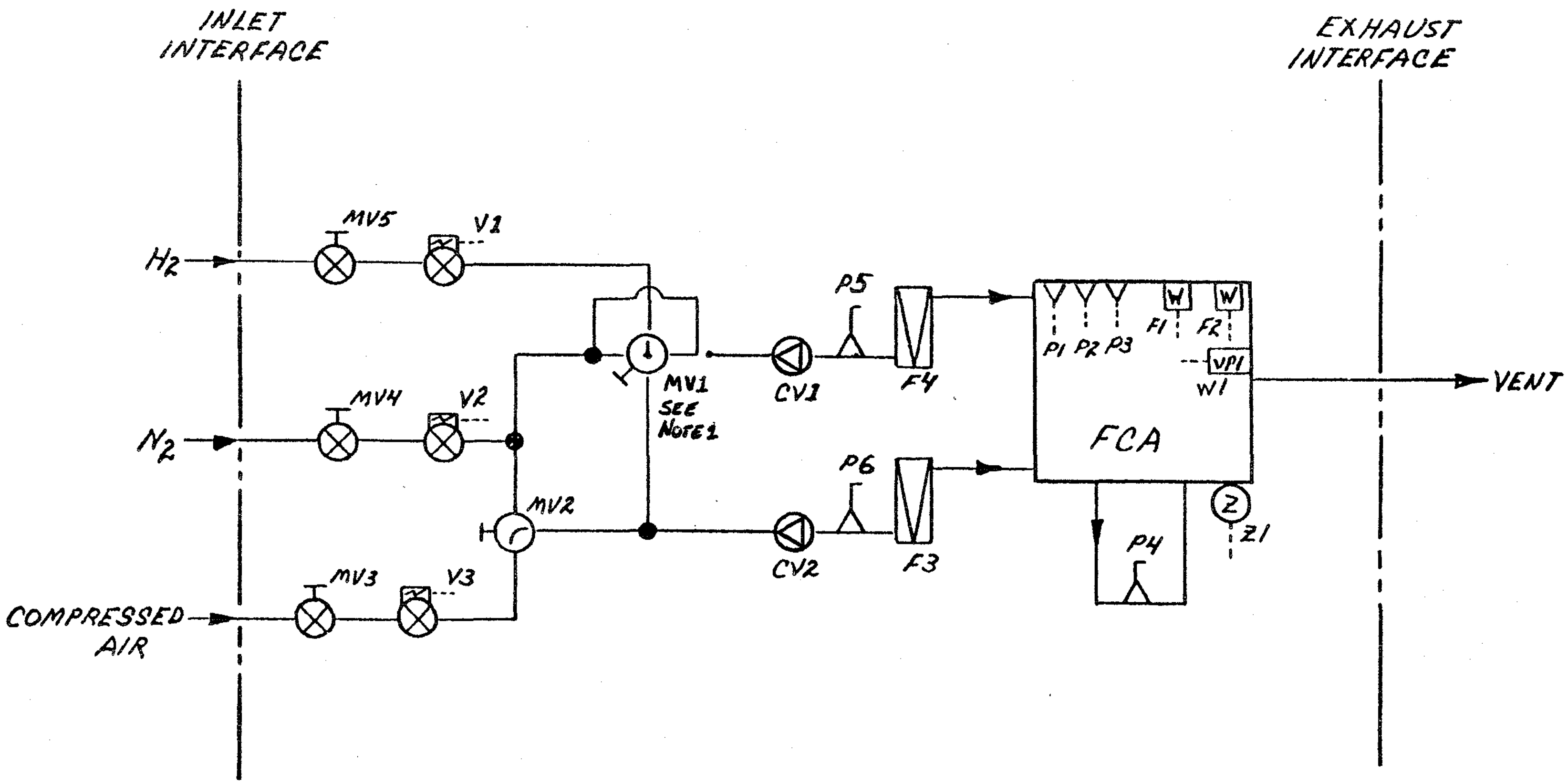


FIGURE 43 FLUIDS CONTROL ASSEMBLY TEST STAND



NOTE: MV1 is a 5-way valve, plumbed so that switching from H_2 to air requires passing an N_2 port.

FIGURE 44 FCA TEST STAND MECHANICAL SCHEMATIC

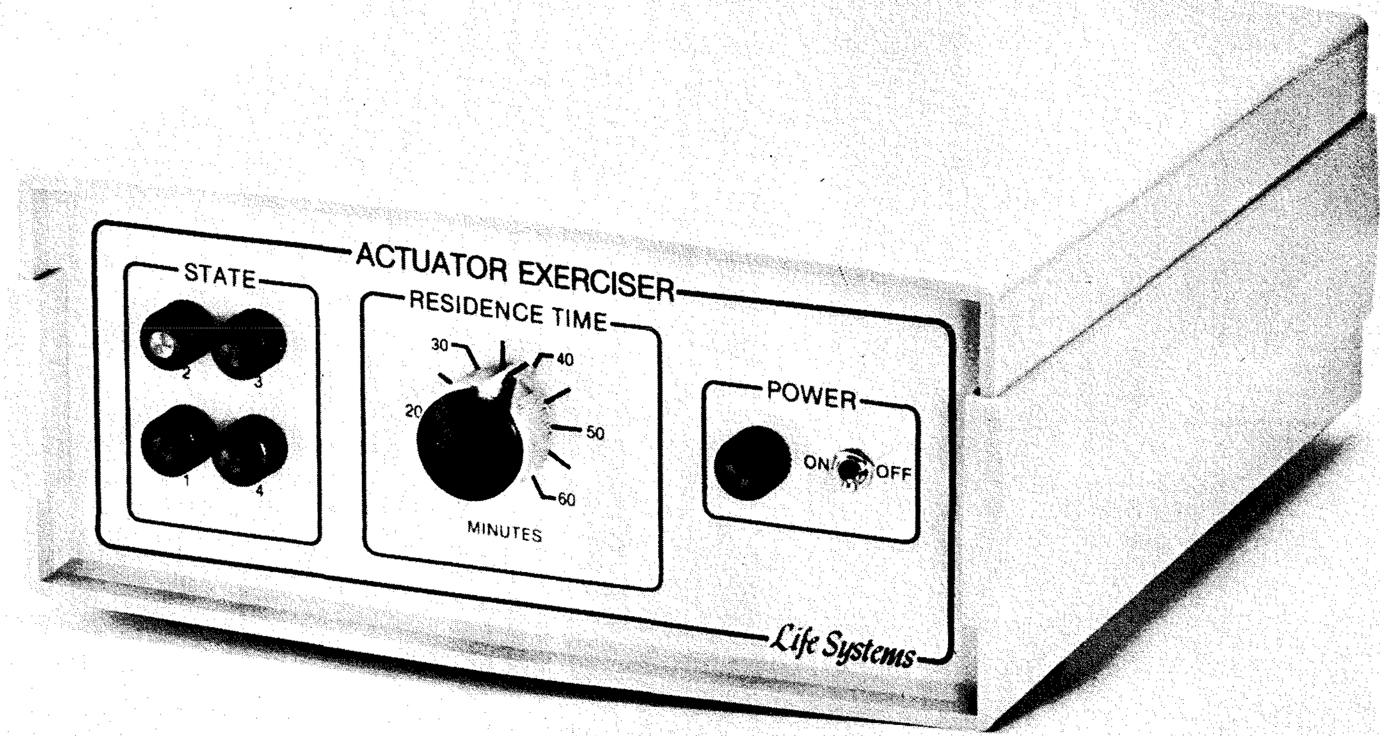


FIGURE 45 ACTUATOR EXERCISER

Test Program

The FCA test program characterized the ability of the FCA to provide consistent operation through multiple cycles. Prior to beginning the testing, the FCA and test stand were integrated and functionally checked. All transducers were calibrated to ensure the generation of accurate test data.

Test Descriptions

The various tests are described below. Conditions are summarized in Table 15.

Checkout Test. As part of checkout testing, all components were inspected as received. After the unit was assembled, an internal to external pressure check was performed. A leak along a thermistor lead for one of the flowmeters was discovered and repaired. The unit was operated for four hours, switching states every 15 minutes, with air at both inlets.

Shakedown Test. The shakedown test was conducted to ensure integrated FCA/test stand operation. Valve positions automatically switched every 60 minutes for 24 hours, with air at both inlets.

Design Verification Test. Most of the DVT was conducted with air at both inlets, although a portion of the testing was done with H_2 feed to the H_2 port to assure simulation of actual operating conditions. The FCA was automatically cycled every four hours through each of its three valve spool positions (high H_2 flow position selected). Each cycle simulates the CO_2 removal subsystem operation from shutdown, through purge to normal, then back to shutdown. This cycle was repeated almost 200 times during testing.

Test Results

The results of over 30 days of continuous testing and nearly 200 complete valve cycles are summarized in Table 16. Additionally, a post-test inspection of the disassembled FCA showed that the general appearance was very good, with no unusual wear or damage to the O-rings. A very slight wear of the VPI cam and follower was noticed, indicating that a lighter follower spring could be used. Overall, the unit performed its mechanical functions well over many cycles.

Conclusions

The FCA is a viable proven vehicle for the reduction of EDC subsystem weight, volume and power consumption.

COOLANT CONTROL ASSEMBLY DEVELOPMENT

Whenever electrochemical modules are to be temperature controlled by a liquid stream, three common elements are utilized: a circulation pump, a diverter valve and a liquid/gas accumulator. This chapter describes development of an integrated CCA to perform these three functions, as depicted schematically in Figure 8.

TABLE 15 FCA SEQUENCE OF TESTS

Item	Description	Duration	Controlled Parameters: Residence Time, min	Controlled Parameters: Gas Selection H_2 Path	Controlled Parameters: Gas Selection N_2 Path	Monitored Parameters
1	Checkout	4 hours	15	Air	Air	P1-P6, F1-F4
2	Shakedown	24 hours	60	Air	Air	P1-P6, F1-F4
3	DVT					
	a. Characterize	6 hours	30	H_2	N_2	P1-P6, F1-F4
	b. Endurance	30 days	60	Air	Air	P1-P6, F1-F4
	c. Characterize	6 hours	30	H_2	N_2	P1-P6, F1-F4

TABLE 16 FCA TEST RESULTS SUMMARY

Parameter	Observations During Nearly 200 Complete Cycles
Valve Positioning	Consistent (as evidenced by flow rate consistency within measurement error). Position indicators functioned satisfactorily.
Valve Spool Torque	Required torque 20% less than motor clutch torque; therefore, somewhat higher valve spool sealing (increased O-ring compression) is permissible.
Valve Leakage	Satisfactory, except for minor leakage from H_2 side to N_2 side during purge mode on occasion (four of 12 observations). Stopped by slight pressure on manual override lever. Increase in O-ring compression (very light - 7% - at present) and possibly less critical positional tolerances are recommended.
Pressure Regulation	Consistent under flow conditions to within ±3% relative standard deviation.
Manual Override Capability	Demonstrated.
Flow and Pressure Measurement[a]	F2, P1, P2 functioned throughout test (F2 after initial sealing of a leak). P3 (redundant sensor) stopped functioning after approximately 100 hours (although resumed satisfactory operation at a point after the test program) and F1 did not function at all. Future use of more reliable sealed (versus exposed chip) silicon pressure sensors and development of improved flow sensor elements is recommended.[a]

(a) The flow and pressure sensors are monitoring components that simply mount in the FCA and, therefore, in themselves, have no critical significance in the basic FCA design. Nonetheless, improvement in these items and/or replacement with more satisfactory versions must ultimately be addressed.

Description

Breadboard

A breadboard CCA was first built with discrete components to verify the grouping of components and the external plumbing interfaces to be made. This consisted of an LSI diverter valve and controller, a pump and an accumulator. This unit functioned successfully and was subsequently incorporated into the six-cell EDCM test stand (discussed in a previous chapter).

In the prototype CCA, an LSI diverter valve, a centrifugal pump and a bladder accumulator were integrated into a single unit weighing 4.2 kg (9.3 lb) and occupying 3,343 cc (204 in^3). Three CCA's fabricated by LSI are shown in Figure 46. A photograph of a disassembled unit is shown in Figure 47.

Both the pump drive motor and the valve drive unit can be removed without breaking into the liquid loop. A pump drive speed sensor is built in to aid in fault diagnosis. The valve drive unit includes a valve position indicator for use with the feedback control electronics. The diverter valve position can be varied manually as well as automatically.

Table 17 contains the CCA Operating Characteristics and Conditions, while Table 18 lists the sensors and actuators of the device. The uses and advantages of the CCA were summarized in Table 6.

Coolant Control Assembly Controller

General Description. The CCA Controller, shown in Figure 48 with the CCA, positions the diverter valve of the CCA in response either to the setting of a potentiometer on the front panel or to an external 0 to 5 V DC signal. Also, the controller provides power shutoff to the pump and diverter valve motor if the signal from the speed sensor of the CCA drops below a preset level.

The CCA Controller is contained in a 9.5 cm (3.7 in) high x 21.6 cm (8.5 in) wide x 23.5 cm (9.3 in) deep plastic enclosure and operates on 115 V 60 Hz power.

Functional Description. The block diagram of Figure 49 shows the relationships among the various functional circuit blocks in the controller. The diverter valve is positioned via a proportional feedback controller. A feedback signal from the position measuring potentiometer (mounted on the diverter valve) is compared with a setpoint signal, which can be provided externally or selected manually. The difference signal, after amplification and proper phasing drives the valve motor in the proper direction until the feedback signal from the position measuring potentiometer equal the setpoint. The valve position is reached at this point.

When the External/Manual switch is in the Manual position the setpoint is obtained from the front panel 10 turn dial potentiometer. The 0 to 5 V DC output of this potentiometer is fed through a setpoint buffer to the controller logic. The setpoint buffer removes loading affects on the 0 to 5 V signal.

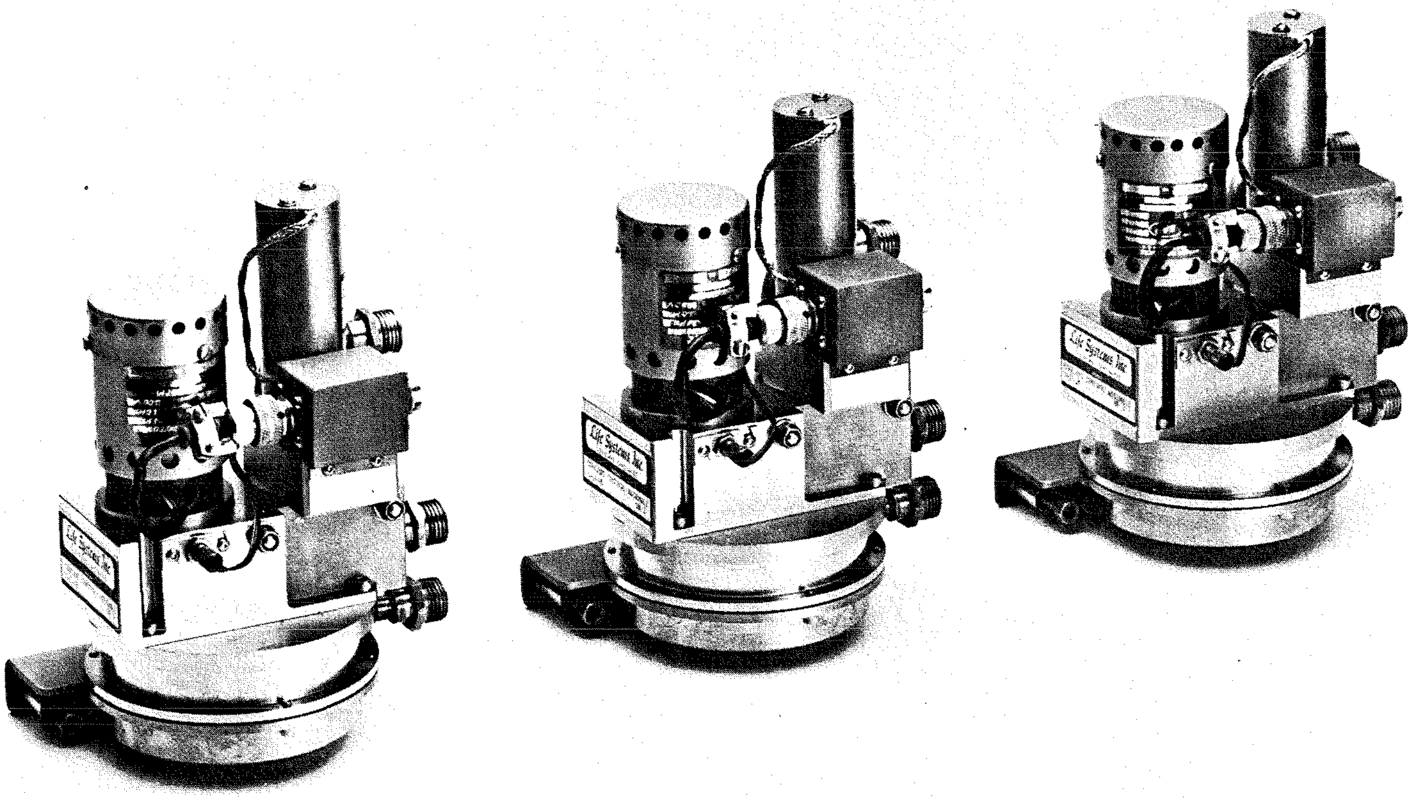


FIGURE 46 COOLANT CONTROL ASSEMBLY

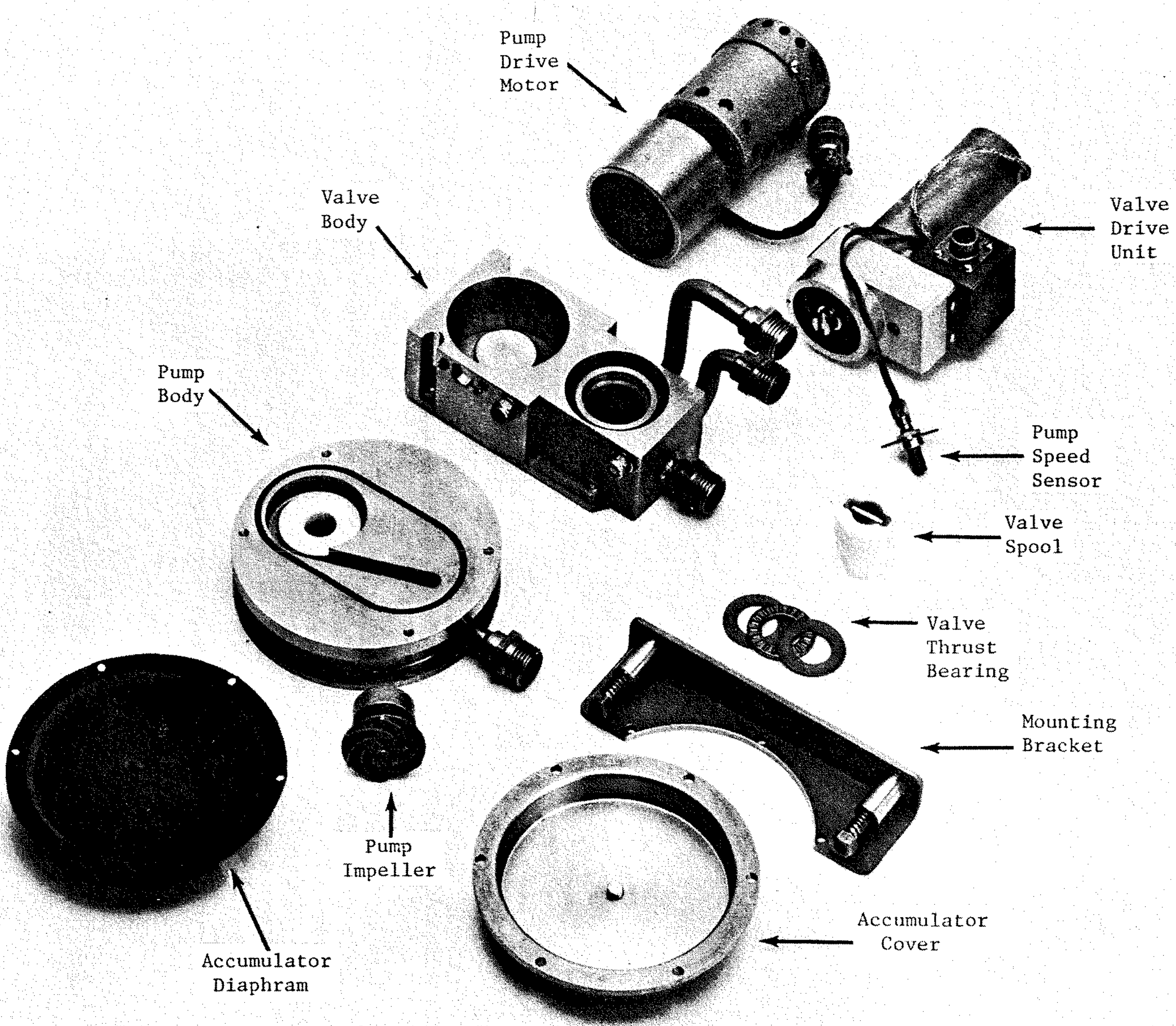


FIGURE 47 COOLANT CONTROL ASSEMBLY - EXPLODED VIEW

TABLE 17 CCA OPERATING CHARACTERISTICS AND CONDITIONS

Water Flow Rate, kg/ h (lb/h)	
Nominal	454 (1000)
Range	409 to 499 (900 to 1100)
Delivery Pressure, kPa (psig)	
Nominal	69 (10)
Range	62 to 76 (9 to 11)
Delivery Temperature, K (F)	
Nominal	296 (75)
Range	289 to 305 (60 to 90)
Liquid Loop Volume, dm^3 (in^3)	
Nominal	2 (122)
Range	1 to 3 (61 to 183)
Pump Speed, RPM	11,000

TABLE 18 CCA SENSOR AND ACTUATOR LIST

Description	Quantity	Redundancy Level	Symbol
Sensor			
Pump Motor Speed (Magnetic)	1	1	S1
Diverter Valve Position (Potentiometer)	1	1	W1
Actuator			
Pump	1	1	M1
Diverter Valve (Variable)	1	1	V1

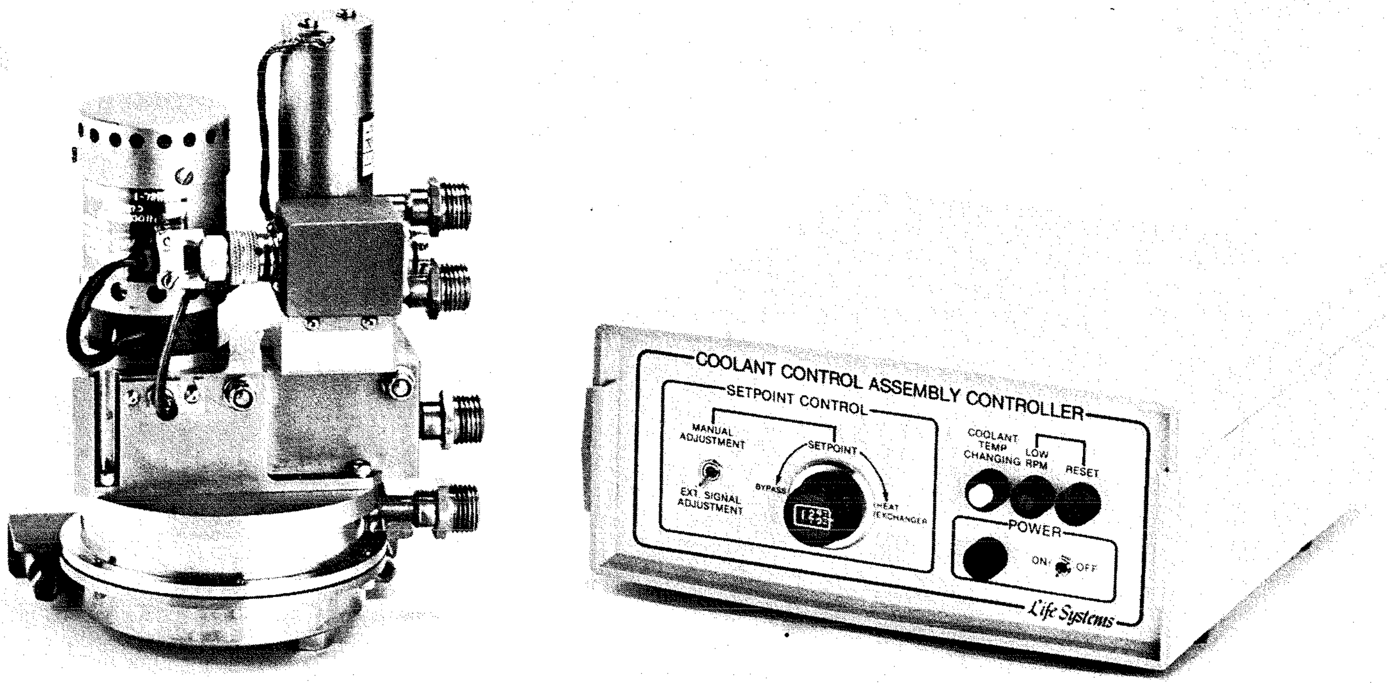


FIGURE 48 COOLANT CONTROL ASSEMBLY AND CONTROLLER

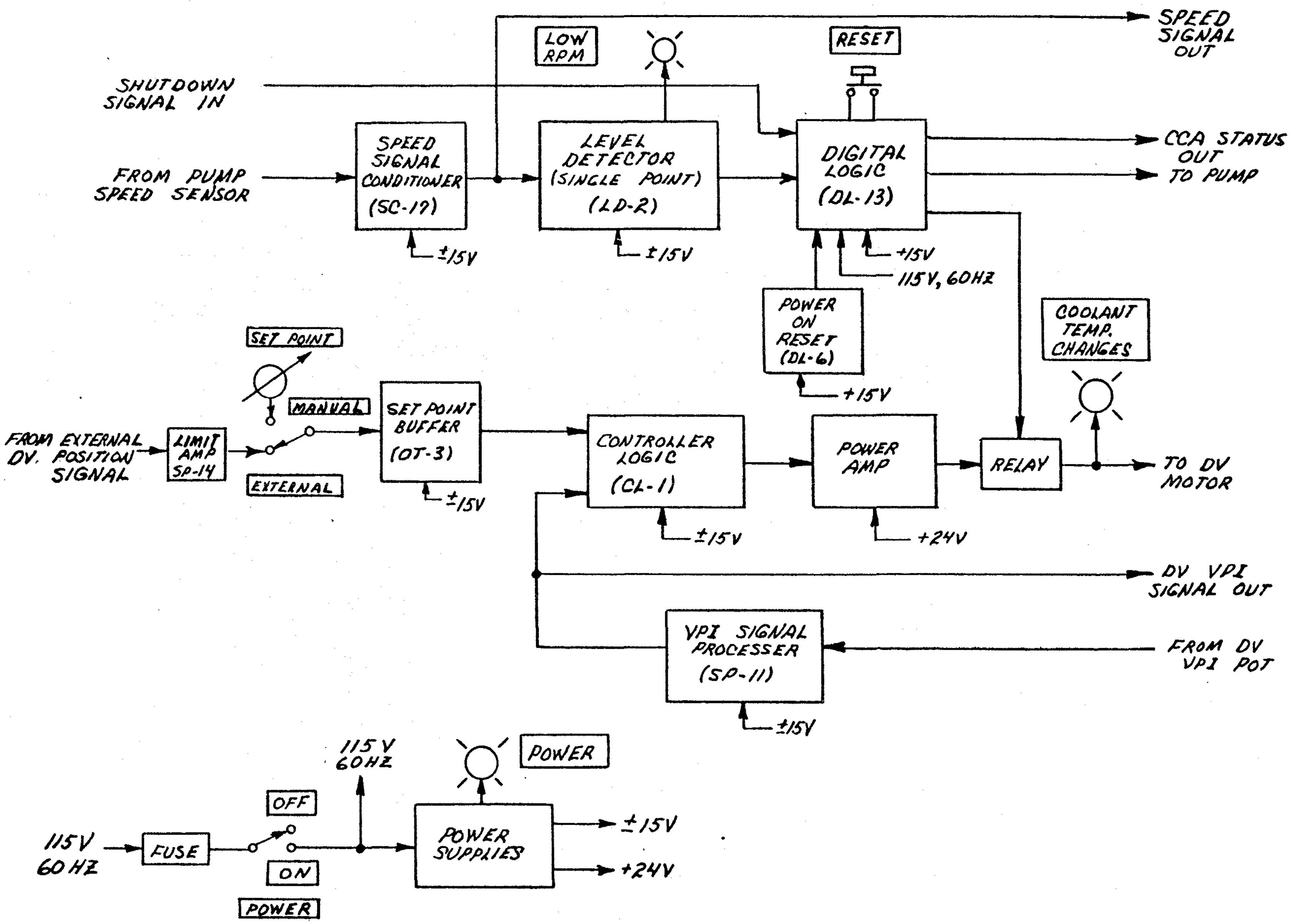


FIGURE 49 CCA CONTROLLER ELECTRICAL BLOCK DIAGRAM

If the External/Manual switch is in the External position, an external 0 to 5 V DC signal replaces the 0 to 5 V DC signal from the front panel dial potentiometer. This external signal is processed through a limit amplifier to prevent its output from going lower than 0 V or higher than 5 V.

The voltage from the Valve Position Indicator (VPI) potentiometer on the diverter valve is processed through the VPI signal processor. The output of this processor is a 0 to 5 V DC signal that corresponds to the two ends of the diverter valve motion range. The constants of the VPI signal processor are tailored to the particular diverter valve that is being controlled.

The 0 to 5 V DC signal from the VPI signal processor is connected to the controller logic. The controller logic produces a signal that is proportional to the difference between the setpoint buffer output and the VPI signal processor output. This difference is voltage amplified, power amplified and sent to the diverter valve motor. The output of the power amplifier is bipolar such that the motor in the diverter valve can rotate in either direction as required.

The signal from the pump speed sensor is conditioned to 0 to 5 V DC and connected to both a rear panel connector and a level detector circuit. The level detector circuit lights a low rpm indicator if the speed falls below the preset level. It also sends a shutdown signal to the digital logic circuit.

When the digital logic receives a shutdown signal (from the level detector or from an external source) it will shut off the power to the pump motor and the diverter valve motor.

Test Support Accessory Development

Test Stand

A test stand was specifically fabricated both to characterize the performance of the CCA and demonstrate its endurance. It is shown pictorially in Figure 50, with the CCA mounted in place, and schematically in Figure 51. The CCA is plumbed between a heat source simulator (HSS), which acts thermally like an electrochemical module, and the liquid/liquid heat exchanger (HX1), which simulates the interface to the spacecraft coolant loop. The CCA controls the simulated module (HSS) temperature by varying the flow of coolant through or around HX1. The CCA varies the flow in response to a 5.0 V signal proportional to the temperature difference between T2 and a setpoint. (The signal comes from a temperature controller, which simulates an analogous control output from a CO_2 removal process C/M I).

Process Simulator

The Process Simulator, shown in Figure 52, was designed to provide an adjustable energy versus time profile to simulate the heat generated by an EDCM. It provides adjustable 0 to 115 V, 60 Hz power to a heater (H1 in Figure 51) located in the HSS. Thermal sequencing is governed by the settings of three front panel dials. The "Energized" dial sets the length of time the heater is energized during an on/off cycle and the "Period" dial sets the duration of

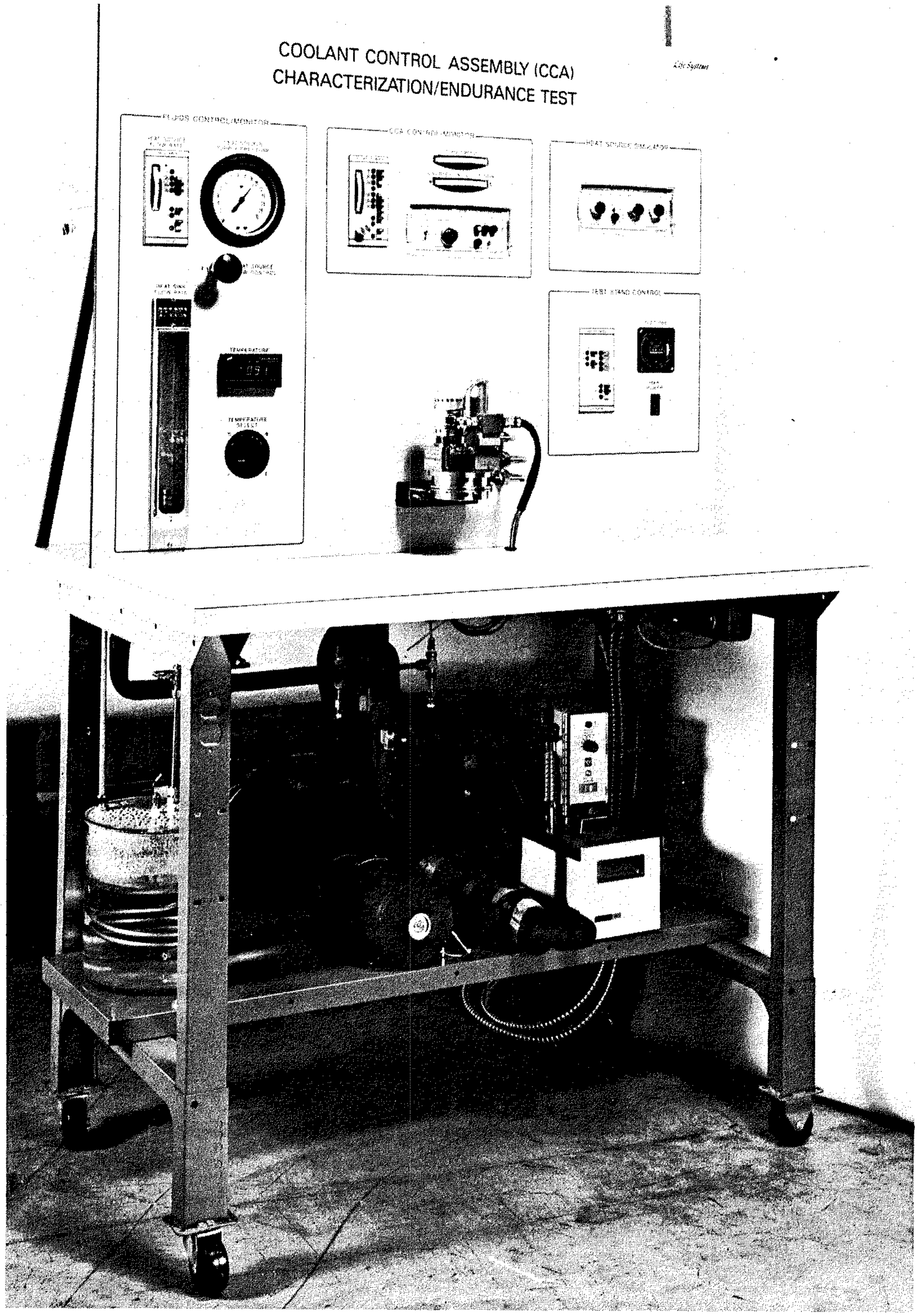


FIGURE 50 COOLANT CONTROL ASSEMBLY TEST STAND

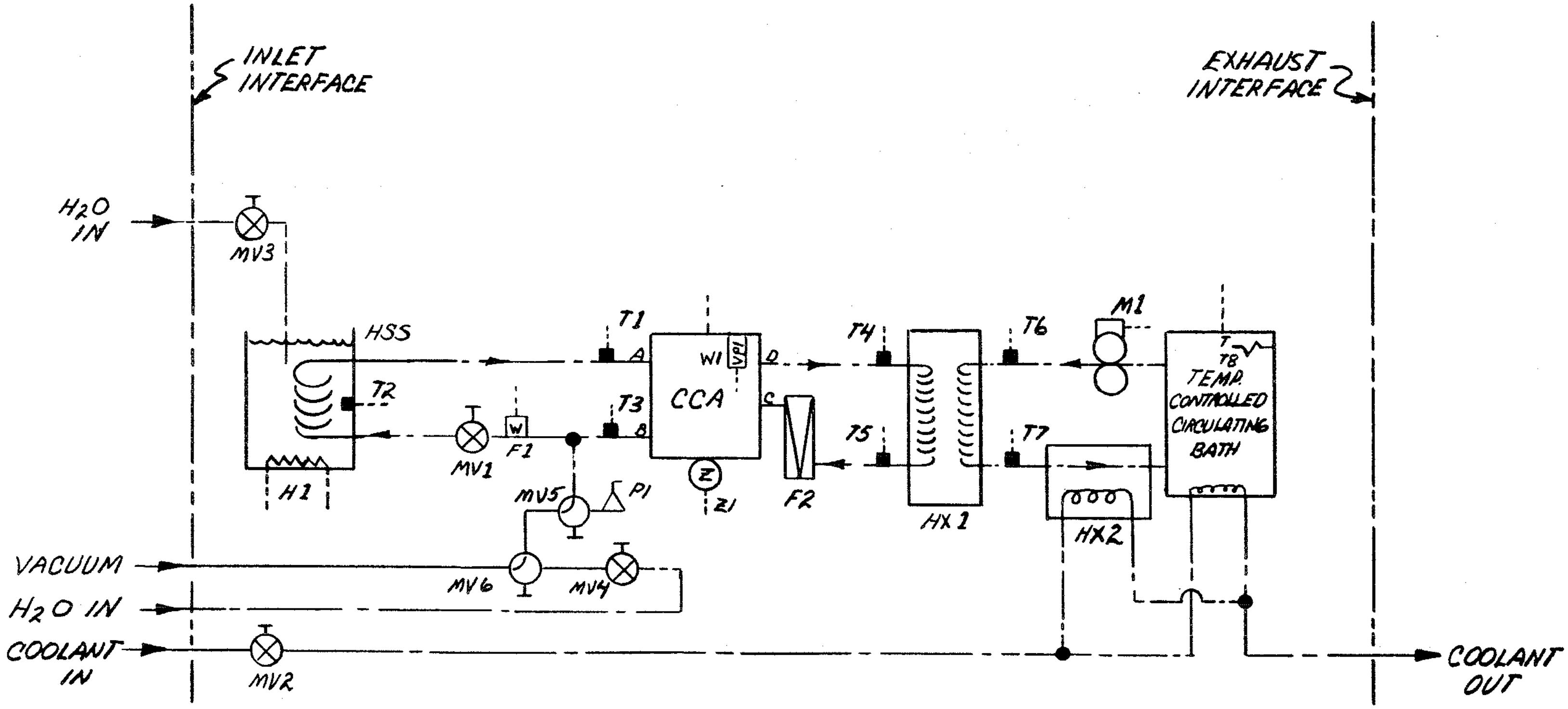


FIGURE 51 COOLANT CONTROL ASSEMBLY TEST STAND SCHEMATIC

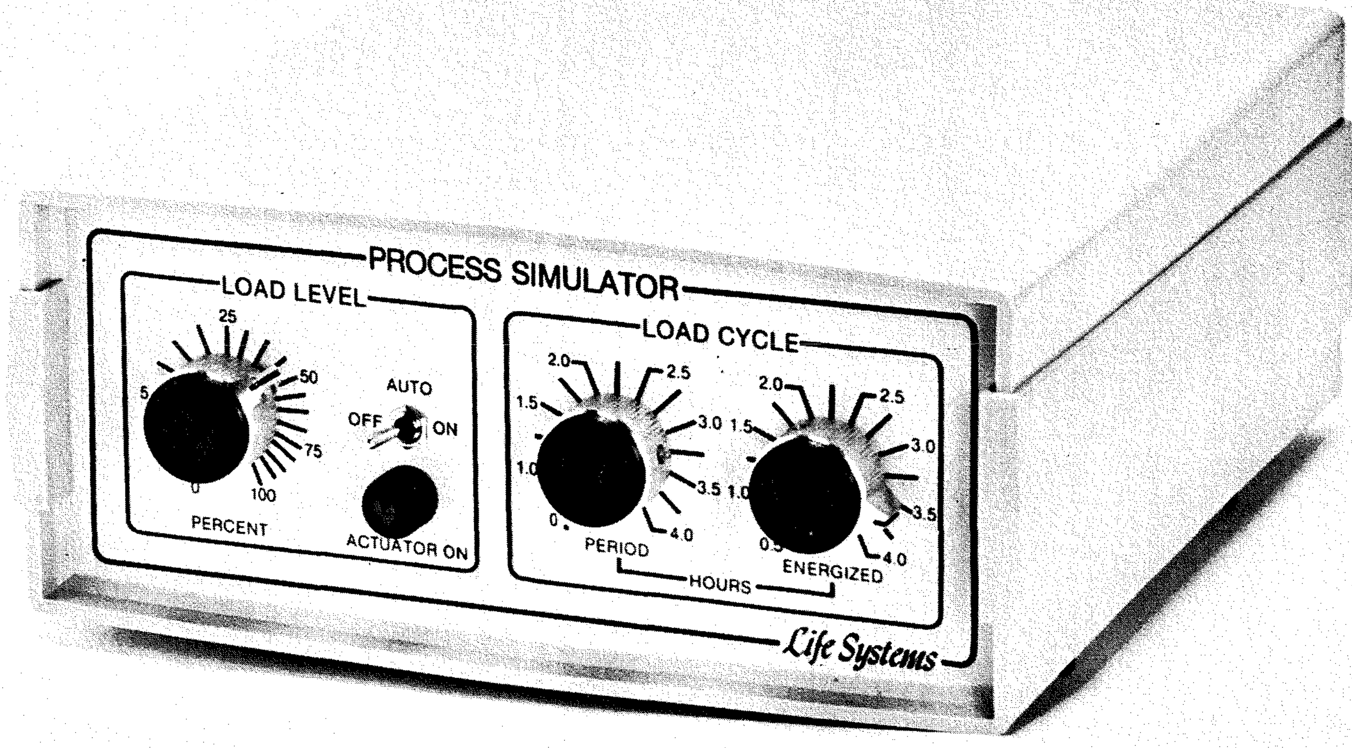


FIGURE 52 PROCESS SIMULATOR

the cycle. Both dials can be set between 0.5 and 4 hours. A third dial, "Load Level," controls the amount of power delivered to the heater during a cycle and has a range of 0 to 100%. An override switch is also provided to override the timer function and allow the load to be powered continuously at the set level.

Test Program

The test program demonstrated the ability of the CCA to maintain constant HSS temperature under variable heat load conditions. Prior to beginning the testing, the CCA and test stand were integrated and functionally checked. All transducers were calibrated to ensure the generation of accurate test data.

Checkout Test

As a part of checkout testing, all components were inspected as received prior to assembly. After the unit was assembled, an internal to external pressure check was successfully performed. The unit was then operated for four hours at nominal conditions.

Shakedown Test

The shakedown test was conducted to ensure integrated CCA/test stand operation and consisted of trial startups and shutdowns and continuous operation at baseline conditions for 24 hours.

Design Verification Test

The DVT both characterized the performance and demonstrated the endurance of the CCA during 30 days of cyclic variations in the heat loading (on-off) by the process simulator. As shown in Figure 53, a typical test cycle, heating caused the diverter valve to shift more of the coolant flow through the heat exchanger to maintain simulated module temperature. When heating was terminated coolant flow gradually shifted back toward the bypass path. This cycle was repeated over 700 times during the testing.

All functions - pump, diverter valve and accumulator - worked well throughout the test period. Figure 54 shows the pump performance for the CCA equipped with a 10,000 rpm motor.

Conclusions and Recommendations

The CCA is a viable proven vehicle for the reduction of electrochemical subsystem weight and volume. Future development efforts should include weight reduction and endurance testing of a directly driven (versus magnetically coupled) pump version.

TECHNOLOGY ADVANCEMENT STUDIES

In Situ Cell Maintenance

This section describes the design of an In Situ Cell Maintenance (ISCM), concept by which an EDC cell can be electrically isolated from the module

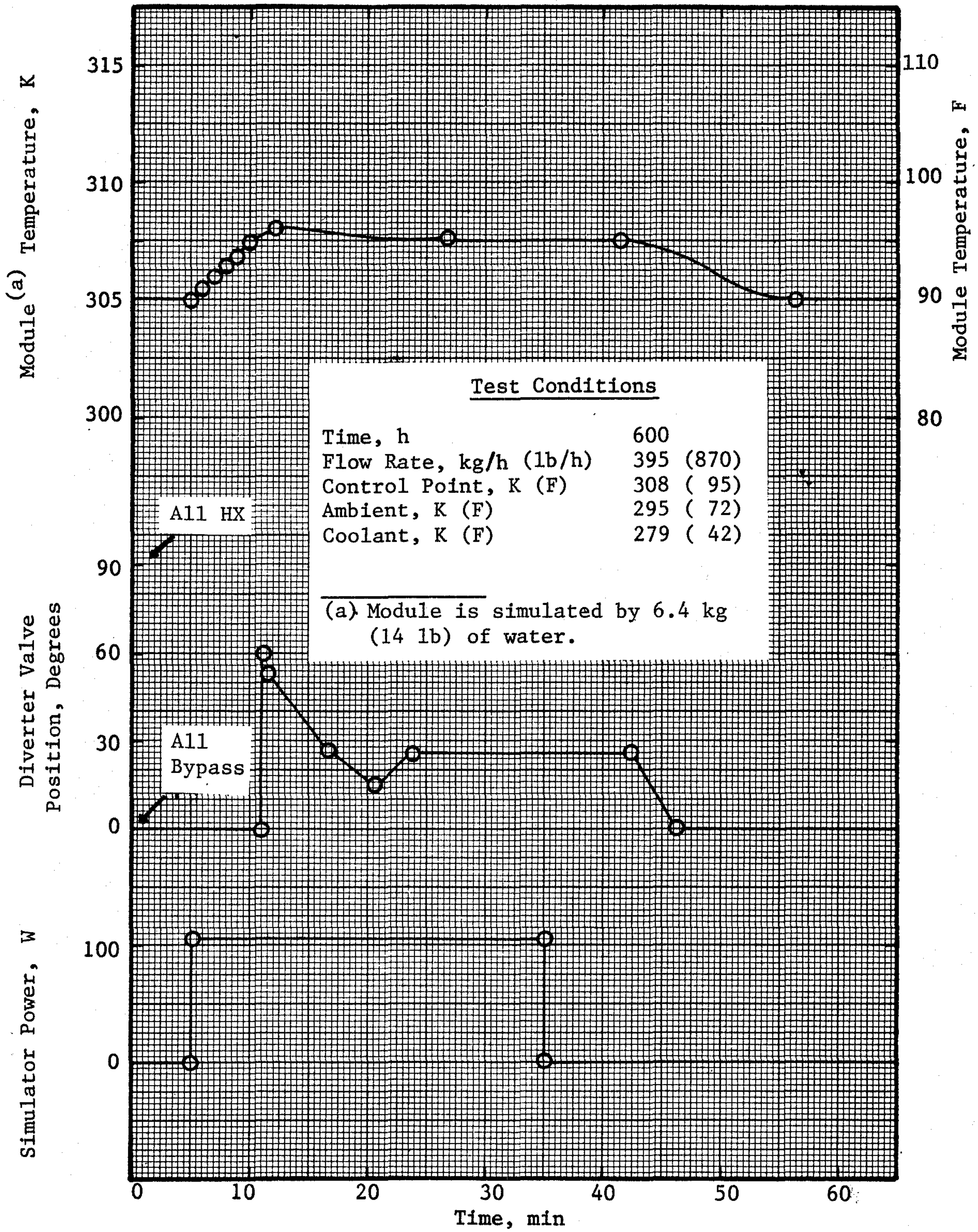


FIGURE 53 CCA TEST CYCLE PERFORMANCE

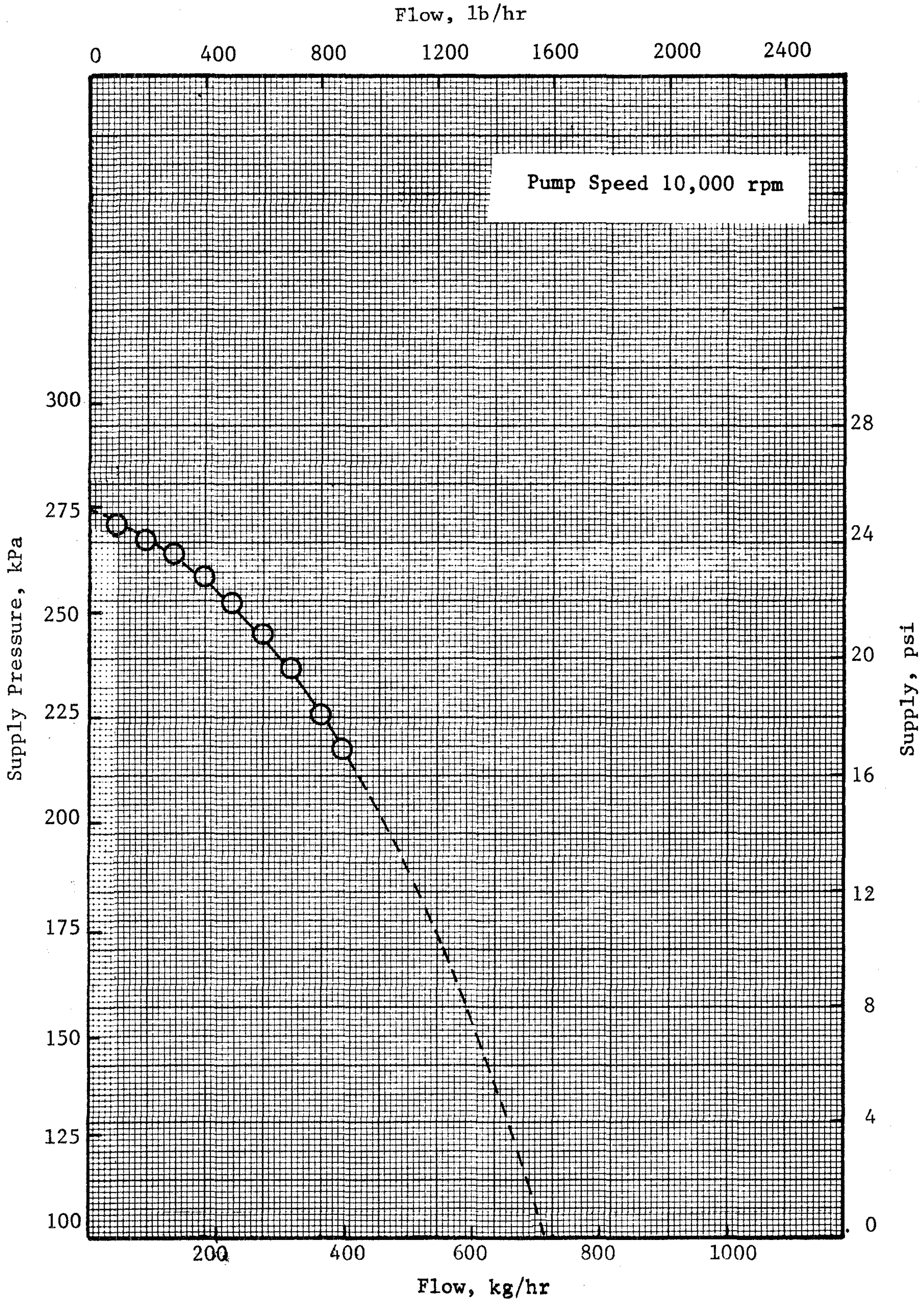


FIGURE 54 CCA PUMP PERFORMANCE

stack while maintaining process air flow. The remaining cells in the module stack would operate normally and the isolated cell would reach an electrolyte volume equilibrium that prevents gas crossover or electrolyte flood out. (See advanced EDCM coolant cavity discussion in Design chapter.)

Background

In the past, the C/M I shut down an EDCM if the electrical performance of any cell deteriorated such that its terminal voltage became unacceptably low (typically less than zero volts). This disabled the entire CO_2 removal process from an air revitalization system when only one cell malfunctioned. A more desirable concept is to electrically isolate only the malfunctioning cell (reduce its current to zero) while the remaining cells continue operation. This can be done manually by altering the wiring that connects the cells in series. Automatic in situ cell maintenance, however, requires that cells be switched using electrical signals.

Design

The schematic diagram of Figure 55 shows a technique which uses relays to do the cell switching. Normally all relays are in their unenergized positions and all cells are carrying current. If cell 3 deteriorates, relay K3 is energized and the current leaving cell 4 (through J7) will bypass cell 3 and go directly to cell 2 through relay K2 and J10. Thus, cell 3 is isolated while all other cells carry current. Any cell or group of cells can be switched out in this manner.

The relays selected are small (about 8.19 cm^3 (0.5 in^3)), sealed aerospace devices which are rated for 25 A DC switching. Their life can be substantially increased and their reliability can be improved if they can be switched with zero current. This will be done by using the following sequence whenever a cell is removed or added:

a. Select cell to be switched
b. Reduce module current to zero
c. Switch cell
d. Return current to previous value

The sequence will take about 100 ms to complete, so module operation will not be adversely affected. Practically, the module will not notice the interruption in current.

Construction

The relays (one for each cell) will be mounted on, and entirely wired through, a heavy duty printed circuit board. Figure 56 shows a board with six relays for a six cell module. The entire card is "plugged into" the advanced composite cell module. The male current pins of each cell mate with high current, commercially available, military-style female connectors on the card. A 10 pin connector is provided to carry the relay coil signals from the C/M I. The two current carrying leads (with terminals) are bolted to the PC card.

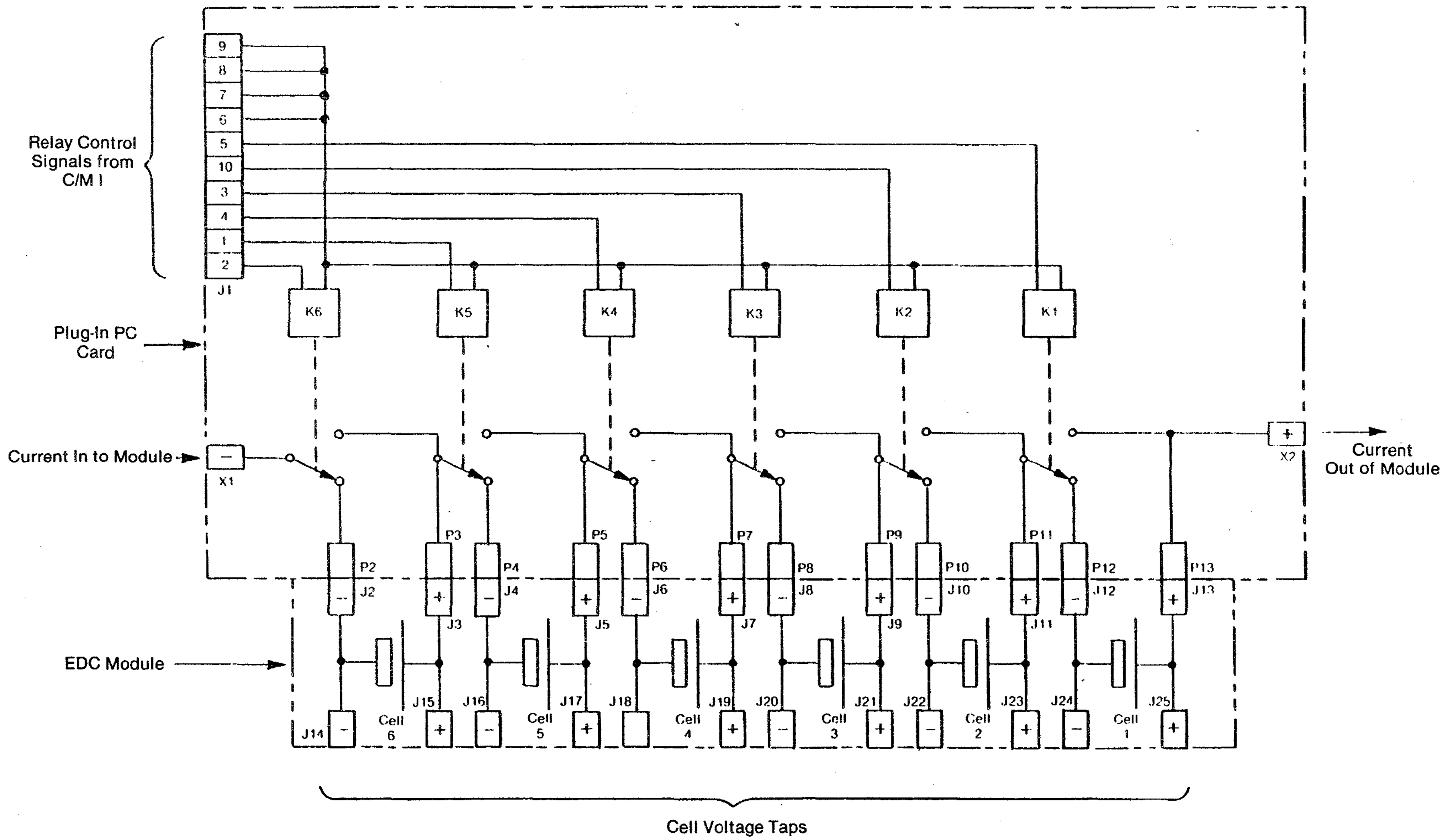


FIGURE 55 ELECTRICAL CIRCUIT SCHEMATIC DIAGRAM FOR EDCM IN SITU CELL MAINTENANCE

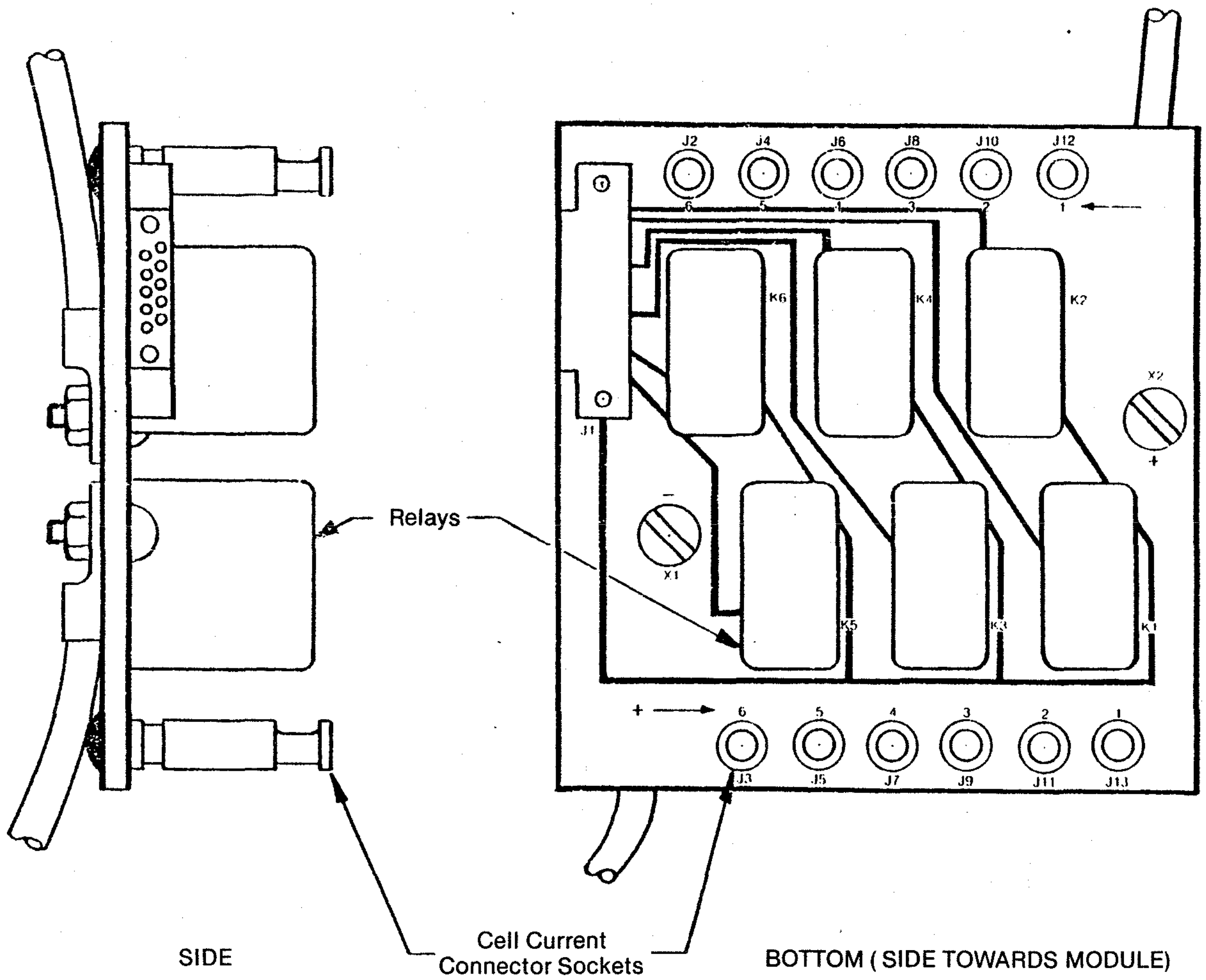


FIGURE 56 IN SITU CELL MAINTENANCE RELAY BOARD

EDCM Charging Facility Development

An EDCM electrolyte charging facility was designed and fabricated to enhance performance reproducibility by reducing charge irregularities between individual cells. The charge facility consists of a system of interconnected valves, tubing, and gauges that permit EDCM pressurization, evacuation, and electrolyte charging. A photograph of the EDCM charge facility appears in Figure 57, and a system schematic diagram appears in Figure 58. The charge facility valves can be positioned to provide the following functions: module charging, module flush- through, module ambient draining, module pressure draining and module pressure check. Testing of the charging facility demonstrated that it performed well as designed.

MINI-PRODUCT ASSURANCE PROGRAM

A Mini-Product Assurance Program was established, implemented and maintained throughout all phases of contractual performance including design, purchasing, fabrication and testing.

Quality Assurance

Quality Assurance activities were included during the design studies, interface requirement definition and during inspection of fabricated and purchased parts. The objective was to search out quality weaknesses and provide appropriate corrective action. Quality Assurance activities for the program included (1) a materials control effort which provided, as a goal, selection of materials of construction which would comply with projected spacecraft material specifications, (2) a configuration management effort, implemented with a primary goal of controlling configuration according to Life Systems' standard drawing and change control procedure, and (3) inspections to provide control over the special processing required in the fabrication of certain cell parts and ensure that workmanship was consistent with the program at the development level. The Quality Assurance program included the preparation of a formal Quality Assurance Plan.

Reliability

Reliability personnel participated in the program to ensure (1) proper calibration of test equipment and TSA instrumentation, (2) adherence to test procedures and (3) proper recording and reporting of test data and observations. A survey of the component, subsystem and TSA designs was performed to determine the calibration requirements for testing. Appropriate components were calibrated during assembly and after installation.

A test procedure was established to ensure that all critical parameters were properly monitored and that the testing conformed to the program's quality assurance and safety procedures. All major testing required that a test plan be completed and reviewed.

Documentation prepared as part of the reliability program included a mini-Single Points Failure Analysis and a mini-Limited Life Items Analysis.

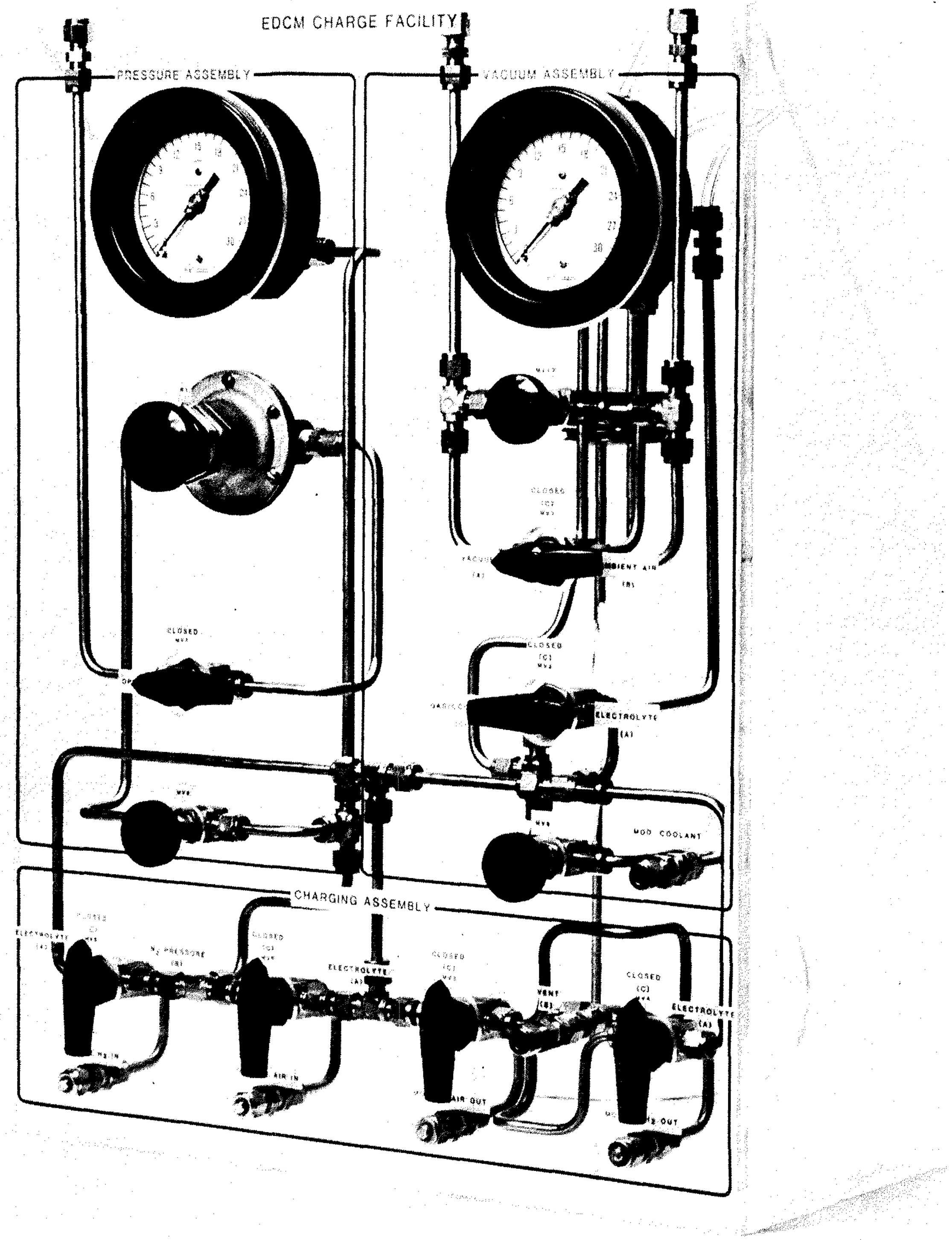


FIGURE 57 EDCM CHARGE FACILITY

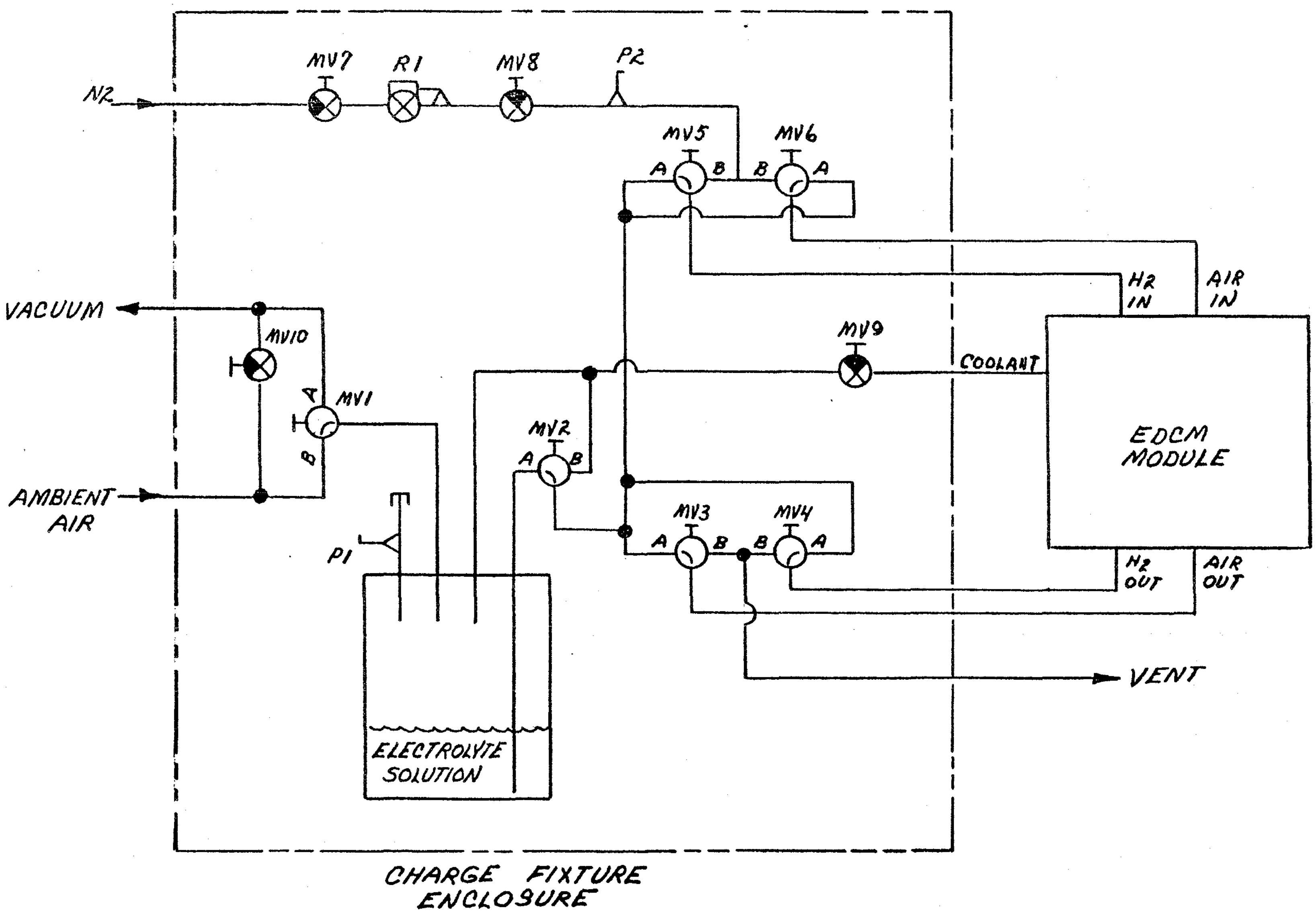


FIGURE 58 EDCM CHARGE FIXTURE SYSTEM SCHEMATIC

Maintainability

A maintainability function was carried out during the design phase of the program. The emphasis was on configuring the module hardware and test stand components for accessibility if unscheduled maintenance were to be required. The Maintainability Program was designed to consider "hands off" operation as the design goal, except for routine maintenance required during the CS-1 testing.

Documentation prepared as part of the mini-Maintainability Program included (1) an Analysis to Avoid Shutdowns, (2) a Fault Detection/Isolation Analysis (FDIA) and (3) a Maintainability Analysis.

Servicing

The test stand has been designed so special servicing is not required.

Scheduled Maintenance

There are two scheduled maintenance procedures required for the test stand. The inlet and outlet process air dew point sensors should be cleaned once each month. The gas humidifier air and water filters should be cleaned or changed every two months.

Access for Maintainability

The EDC module was packaged for ease of accessibility should a malfunction occur.

Safety

A Safety Program was initiated to ensure adherence to safety standards and procedures essential to protect personnel and equipment. The program consisted of identifying possible adverse subsystem and TSA characteristics, reviewing designs and design changes for potential safety hazards, reviewing NASA Alerts for safety information and incorporating the equipment's protective features. Features designed to protect the equipment included (1) automatic, fail-safe shutdown to prevent operation under conditions that would damage the equipment, and (2) a circuit breaker to protect source of power and to prevent internal equipment from additional damage due to fault-causing, high current loads. Features designed into the hardware to protect personnel included (1) no sharp edges which are exposed on the inside or outside of the hardware and (2) fluid lines which are stainless steel to avoid fluid contamination.

Documentation prepared as part of the safety program included Safety Design Criteria and a Safety Hazard Analysis.

CONCLUSIONS

The following conclusions are a direct result of the program studies.

1. The prototype CS-1, sized for one-person CO_2 removal capacity, is projected to weigh 35.2 kg (77.4 lb), have a subsystem volume of

0.062 m^3 (2.2 ft^3), consume 91 W of power for operation of major components while producing 27 W of DC power from the electrochemical process. The subsystem should generate 132 W (450 Btu/h) of heat.

2. The minicomputer-based Series 100 C/M I designed during this effort will not only operate the CS-1 subsystem, but will also provide flexible, developmental capabilities, including multiple front panel user interfaces. However, it is projected that the basic CS-1 control and monitoring capabilities will be likely provided by a flight-version microcomputer-based C/M I preprototype due to technology advances in a parallel contractual effort. This C/M I is projected to weigh only 16 kg (35 lb), occupy 0.28 m^3 (1.0 ft^3) and consume 50 W of power.

3. The prototype FCA will satisfy the fluid handling requirements of EDC-based CO_2 removal subsystems with a 91% reduction in the number of components (to one), a 69% reduction in the number of connections (to a total of five), a 64% reduction in the weight of the subsystem (to less than 1.8 kg (4 lb)), a 71% reduction in component volume (to 2.0 dm^3 (120 in^3)) and a 75% reduction in component power requirements (to 20 W).

4. The breadboard CCA design demonstrated the capability to satisfy the coolant loop requirements of a liquid-cooled EDC-based CO_2 removal subsystem with a 67% reduction in the number of components (to one), a 43% reduction in the number of connections (to four), a 26% reduction in the component weight (to 4.2 kg (9.3 lb)), a 56% reduction in the component volume (to 3.9 dm^3 (240 in^3)) and a 37% reduction in the power (to 86 W).

5. The unitized core electrochemical cell design has successfully demonstrated reproducible, predictable high level performance over extended ranges in RH and H_2 backpressure. Superior, stable CO_2 removal efficiencies consistently averaging greater than 90% were observed during this period over a 16 to 72 RH range for CO_2 partial pressures of 400 Pa (3.0 mm Hg). This included 700 hours of dry-range operation, at 16 to 24% RH, with no degradations. Techniques to ensure that air entering the EDCM is at module temperature are also partly responsible for this performance. The nominal cell voltage was 0.4 V. The unitized core cells can withstand 103 kPa (15 psid) differential pressures (maximum requirement) with no leakage either through or around the matrices.

6. The composite cell frame design for CS-1 subsystem EDCM will provide prototype hardware maturity by including the following features.

   a. Air temperature preadjustment for increased RH tolerance
   b. Integral air manifolds
   c. Unitized cell cores
   d. Sealed coolant cavities integral with cell frames for improved thermal, electrical and reliability characteristics
   e. Foil current collectors at both anode and cathode

f. Reliable, proven current connection pins
g. Minimization of H_2 pressure drops
h. Improved manufacturing characteristics

7. The In Situ Cell Maintenance concept for increased EDCM reliabilities has been defined. It includes compact, automatically switched relays to electrically isolate degraded cells. The integrated electrical design will minimize space requirements and resistive power losses. The CS-1 composite cell design, with its allowance for a temperature difference between coolant and anode during operation, will avoid cell dryout during shutdown, during which the temperature will drop to compensate for terminated water production.

RECOMMENDATIONS

It is recommended that the current program be extended and focused on building a prototype CO_2 removal subsystem based upon the CS-1 concept. This subsystem development effort would integrate all the performance advances and hardware developments into a single, self-contained engineering prototype consisting of a mechanical/electrochemical assembly and electrical/electronic assembly. The objectives of the proposed tasks are to fabricate, assemble and test a prototype CS-1 subsystem, including the advanced composite cell/unitized core EDC module, a prototype FCA, a prototype CCA and a Series 200 C/M I. This prototype can then be evaluated as an independent subsystem for integration into the Shuttle Air Revitalization System (ARS) for the Extended Duration Orbiter (EDO) missions.

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1. Report No.
NASA CR-166141

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Advanced Electrochemical Depolarized Concentrator Cell Development

5. Report Date
December, 1981

6. Performing Organization Code

7. Author(s)
F.H. Schubert, T.M. Hallick, and E.P. Koszenski

8. Performing Organization Report No.
LSI-TR-379-4

10. Work Unit No.
T-4582

9. Performing Organization Name and Address
Life Systems, Inc.
24755 Highpoint Road
Cleveland, Ohio 44122

11. Contract or Grant No.
NAS-2-10204

13. Type of Report and Period Covered
Contractor Report

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

14. Sponsoring Agency Code
199-60-12-04

15. Supplementary Notes
Point of Contact: Phillip D. Quattrone, M/S 239-4
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Moffett Field CA. 94035 COMM:415-965-5733

16. Abstract
This program included (1) the design of an advanced Carbon Dioxide Removal Subsystem and development and evaluation of (2) a full-scale (six-cell), Electrochemical Depolarized Carbon Dioxide module with unitized core composite cells, (3)a fluids control assembly,that integrates eleven discrete components, (4) a Coolant Control Assembly that replaces three components and interconnecting plumbing and (5) Test Support Accessories and instrumentation required for component testing and required test stands and test setups. A detailed hardware concept for automatic electrical isolation of degraded Concentrator cells was also developed, and an improved facility for electrolyte charging of Concentrator cells was developed and tested.

Parametric testing of the six-cell module demonstrated high level, repeatable performance over 3000 hours of operation and relative humidity variations tween 16 and 72 %.Average carbon dioxide removal efficiency was typically greater than 90 % (versus the 80 % design point) at a nominal carbon dioxide partial pressure of 400 Pa (3.0 mm Hg). The cell voltage was 0.4 V. The cell could sustain 965kPa (140 psid) hydrogen/air differential pressures with no leakage.

The Coolant Control Assembly performed at or above design point levels over 700 typical test cycles. The Fluids Control Assembly demonstrated satisfactory mechanical performance over 30 days of continuous testing and (over)

17. Key Words (Suggested by Author(s))
carbon dioxide removal,
coolant control assembly,
fluids control assembly

18. Distribution Statement
unlimited
STAR category 45

19. Security Classif. (of this report)
unclassified

20. Security Classif. (of this page)
unclassified

21. No. of Pages
115

22. Price*

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